IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received February 12, 2020, accepted February 27, 2020, date of publication March 2, 2020, date of current version March 16, 2020.

*Digital Object Identifier 10.1109/ACCESS.2020.2977716*

# A Review on Applications of Capacitive Displacement Sensing for Capacitive Proximity Sensor

**YONG YE[1,2], CHIYA ZHANG[3], (Student Member, IEEE), CHUNLONG HE[1], (Member, IEEE), XI WANG[2], JIANJUN HUANG[1], (Member, IEEE), AND JIAHAO DENG[4]**

[1]Guangdong Key Laboratory of Intelligent Information Processing, Shenzhen University, Shenzhen 518060, China
[2]Department of Production Engineering, KTH Royal Institute of Technology, 114 28 Stockholm, Sweden
[3]School of Electronic and Information Engineering, Harbin Institute of Technology, Shenzhen 518055, China
[4]School of Mechatronical Engineering, Beijing Institute of Technology, Beijing 100081, China

Corresponding author: Chiya Zhang (chiya.zhang@foxmail.com)

This work was supported in part by the Natural Science Foundation of China under Grant 61902252, in part by the Shenzhen Overseas High-level Talents Innovation and Entrepreneurship under Grant KQJSCX20180328093835762, in part by the Natural Science Funding of Guangdong Province under Grant 2018A030310509, and in part by the Science and Technology Innovation Commission of Shenzhen under Grant JCYJ20190808122409660.

**ABSTRACT** Capacitive proximity sensors (CPSs) are ubiquitous because of their simple design, low cost and low consumption. Capacitive displacement sensing, as one of the three sensing modalities, works for long distance and can be unitized to measure more physical quantities compared with capacitive volume and deformation sensing. In this paper, we firstly introduce the concept of capacitive displacement sensing. After that, we present applications of capacitive displacement sensing under three broad categories: distance measurements, indirect measurements, and the applications applied in smart environments. Finally, we discuss the challenges and possible solutions for CPSs development. We show that both the detection range and accuracy of CPS can be improved by multi-sensor fusion, and the application scenarios can be extensive through machine/deep learning approaches. We aim to provide a comprehensive, and state-of-the-art review of the capacitive displacement sensing, and inspire more researchers and developers to find wide application perspectives.

**INDEX TERMS** Capacitive proximity sensor (CPS), capacitive displacement sensing, distance measurement, indirect measurement, smart environment.

## I. INTRODUCTION

Proximity detection is an important measurement task that detects the information of nearby objects without physical contacts. A proximity sensor often looks for the change in the field of electromagnetic (capacitive sensor, electrostatic sensor, magnetic sensor) or electromagnetic radiation (infrared) or light (visual Sensor) to perceive the objects. Compared with other proximity sensors, capacitive sensors offer many desirable properties, e.g. low cost, low energy consumption [1], and flexible and variable structure design. Especially in smart environment applications, CPSs have an important portion thanks to these desired properties. Figure 1 shows the growing number of publications that involve CPS over the past two decades. From 1998 to 2018, the annual growth of publications on peer review was 17% on average.

The associate editor coordinating the review of this manuscript and approving it for publication was Miltiadis Lytras.

CPSs use electric fields to detect objects with different sensing modalities. The sensor response results from the change in dielectric constant around the working electrodes, or the change of relative position between the working electrodes, or between the object and the working electrodes which is the dividing basis of the sensing modalities. As shown in Figure 2, CPSs in displacement sensing modality can detect the objects at a large distance and also measure more physical quantities compared with capacitive volume and deformation sensing. Volume sensing can be applied in measurements of dielectric constant, gas component, relative humidity, voltages or imaging. Deformation sensing and displacement sensing can be not only used for direct measurements (e.g. linear or angular displacement), but also

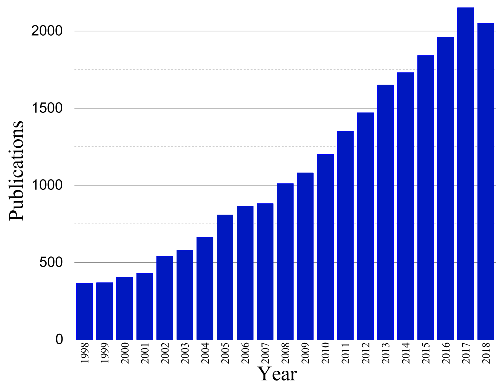



**FIGURE 1.** The increasing number of publications in capacitive sensors from 1998 to 2018. (Data from Google scholar advanced search: allintitle: "capacitive sensor".

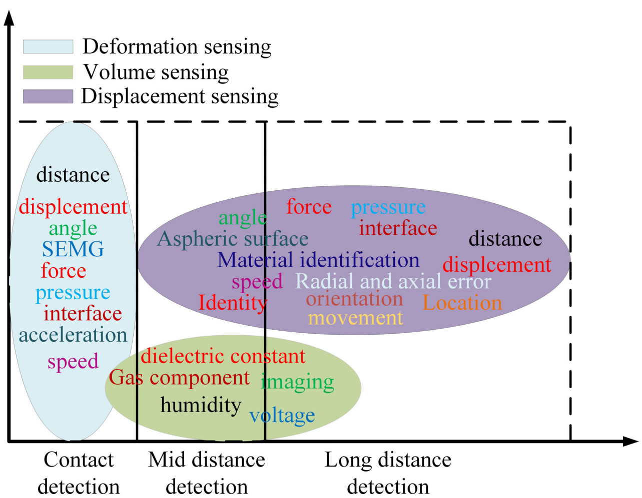



**FIGURE 2.** Working distance and measurement physical quantities of the there sensing modalities.

for indirect measurements (e.g. force, speed, acceleration and so on). In addition, in displacement sensing modality, CPSs can be unitized to classify materials and recognize the surface profiles of objects based on object distance features. However, the precise theoretical model is much challenging in this sensing modality. Besides, the nonlinear relationship between capacitance and object distance leads to difficulties in precise measurements. In recent years, the development of machine/deep learning approaches has provided another perspective to remarkable breakthroughs and research possibilities. This paper focuses on capacitive displacement sensing in actual measurements using machine/deep learning approaches.

- **Difference from other related reviews**

Several reviews on capacitive sensors have been published in recent years [3]–[8]. Their focuses are summarized as follows:

**1. Design of Multi-channel Fringing Electric Field Sensors for Imaging (Part I and II) [3], [4]**: The authors used two papers to summarize and analyze the figures of merit of capacitive sensors, such as penetration depth, signal strength, measurement sensitivity, and imaging resolution. These papers provided intuitive guidelines for sensor design.

**2. Planar capacitive sensors-designs and applications [5]**: This review helps readers build a basic knowledge hierarchy of planar capacitive sensors, such as "what is a planar capacitive sensor?", "what are the operation modes, how do they work, and where are the pros and cons of each operation mode?" and "what are the factors influencing the sensitivity distribution of a planar capacitive sensor".

**3. A review of nanometer resolution position sensors: Operation and performance [6]**: This paper reviewed the state-of-the-art in nanometer resolution position sensing technologies, including resistive, piezoelectric and piezoresistive strain sensors, capacitive sensors, electrothermal sensors, eddy current sensors. It presents an analysis of the principle, the readout circuits, the linearity error and the electronic noise for readers.

**4. Advances in capacitive, eddy current, and magnetic displacement sensors and corresponding interfaces [7]**: This paper presented the latest advances of capacitive, inductive and magnetic sensors for displacement measurement in micrometer, nanometer, and sub-nanometer scales. The authors mainly discussed the MEMS capacitive displacement sensors and the relative interface/readout circuits.

**5. Finding common ground: a survey of capacitive sensing in human-computer interaction [8]**: After years of development, capacitive sensing has been used for human-computer interaction and has become ubiquitous on mobile, wearable, and stationary devices for interaction. This review summarized the taxonomy (e.g., active vs. passive sensing and operating modes) for capacitive sensing and discussed the ongoing research challenges, and grouped the 193 past papers by application scenarios, and helped readers to find possible future applications in the field of human-computer interaction.

In this paper, we will review the literature on CPS in displacement sensing modality and give an overview: from the related definition, to the physical functioning principles. We will group the applications of capacitive displacement sensing according to measurements of physical quantities. We will pay particular attention to the most recent advancements based on machine or deep learning approaches. The review is to contribute a useful framework of capacitive displacement sensing to save time and efforts for researchers and developers, and to inspire them to find the wide application perspectives.

The rest of this paper is organized as follows. In Section II, we introduce the basic knowledge of capacitive displacement sensing. Section III describes the three broad categories of the applications. Some recent advancements and innovations will be reviewed and highlighted. In section IV, we present the challenges and give an outlook for the possible future ones. Finally, we conclude the review.

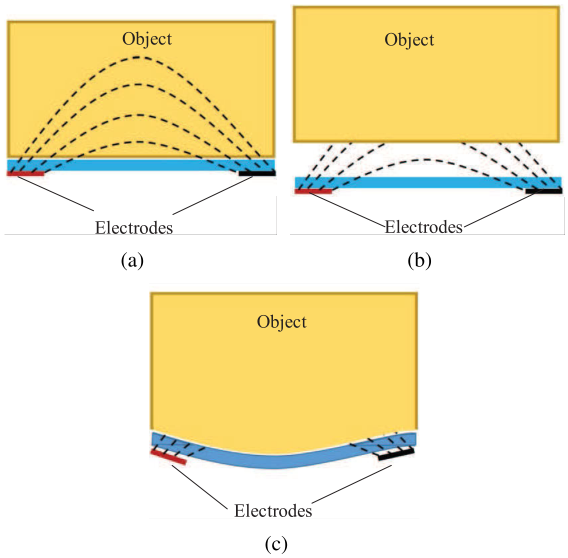



**FIGURE 3.** **Sensitive modalities: (a) volume sensing, (b) deformation sensing and (c) displacement sensing [9].**

## II. BACKGROUND

### A. DEFINITION OF CAPACITIVE DISPLACEMENT SENSING

Capacitive sensing based on capacitive coupling is a technology that can detect and measure anything that is conductive or has a dielectric constant different from the air [10]. For the sensing modality, a CPS is sensitive to the change in dielectric constant or distance between the electrodes, or the electrodes and the objects. Therefore, capacitive sensing can be divided into three types according to sensing modality: volume sensing, deformation sensing and displacement sensing.

(1) Volume sensing: In this sensing modality, the measured capacitance varies with the shape, size, dielectric constant of the object, or the change of the electric field generated by the object itself. Several representative applications in this sensing modality have been proposed, such as electrical capacitance tomography (ECT) [11], capacitive gas sensor [12], [13], capacitive humidity sensor [14], capacitive voltage sensor [15], [16], and so on.

For example, ECT is primarily used for non-invasive imaging by determination of the dielectric permittivity distribution within inaccessible domains from capacitance measurements [17]. Capacitive gas sensors are able to sense many gas like $H_2$, $O_2$, $NO_2$, $NH_3$. The sensors covered with gas sensitive materials are dominated by tracking the change in the dielectric property of the sensing layer upon gas adsorption [18]. Similarly, capacitive humidity sensors are sensitive to the dielectric constant of the sensing layer variations with relative humidity. Capacitive voltage sensors measure the electric field around the charged conductors and thereby determine the potentials on the conductors [16].

(2) Deformation sensing: Here, the capacitance changes caused by the deformation of the electrodes are utilized to measure angle [19], displacement [20], force [21], acceleration [22], muscle action for interaction [23] and so on.

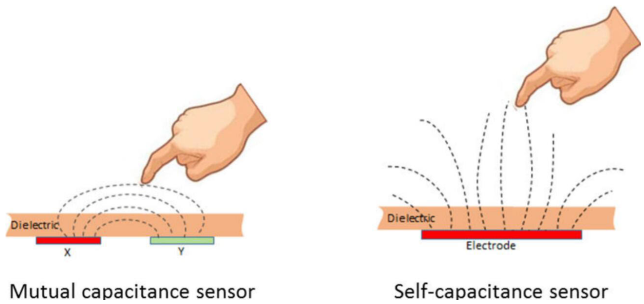



**FIGURE 4.** **Capacitive proximity sensor (CPS) [29].**

Capacitive deformation sensing is grounded on the rotations or the movements between the sensors' electrodes that can be used to measure angular or linear displacements. Moreover, according to the structural properties of the electrodes or some transformation relations between the electrode deformation and the measured physical quantities, it is straightforward to derive the force, the acceleration on the electrodes or the actions as muscle moves from the displacements.

(3) Displacement sensing: As the object being sensed moves a distance from the electrodes, the capacitance changes. The representative applications working in this modality are detections of displacement, distance [24], location [25], movement orientation [27] and human-computer interaction [28].

Capacitive displacement sensing can be used for non-contact measurements of displacement, distance and position, but the detection range of a CPS is affected by the dimension and dielectric constant of the object. Furthermore, when several electrodes are arranged in a regular pattern, we can obtain the location, movement orientation of the object, and some interactive intentions represented by the movement trajectories of a human body according to the different influences of the object on the electrodes from the object distances.

### B. THEORETICAL ANALYSIS

The good design of a CPS relies on understanding of the fundamental principles, and the trade-offs of sensitivity, resolution and signal strength. The sensor structure can influence a measurement, thus it is important to optimize the electrodes' parameters to obtain the highest design priority for a practical application. Therefore some knowledge on the capacitive sensing theory is required.

Conventionally, a traditional capacitor is in the form of a pair of parallel electrodes with a dielectric in between them. A voltage difference applied between the two electrodes results in an electric field between them. This electric field exists not just directly between the electrodes, but extends the area of the overlap. The extended field is known as a fringe field. In general, the fringe field for a parallel electrode capacitor can be neglected as long as the distance between electrodes is much less than the electrode dimensions. When the electrodes gradually open up, the electric field is expanded

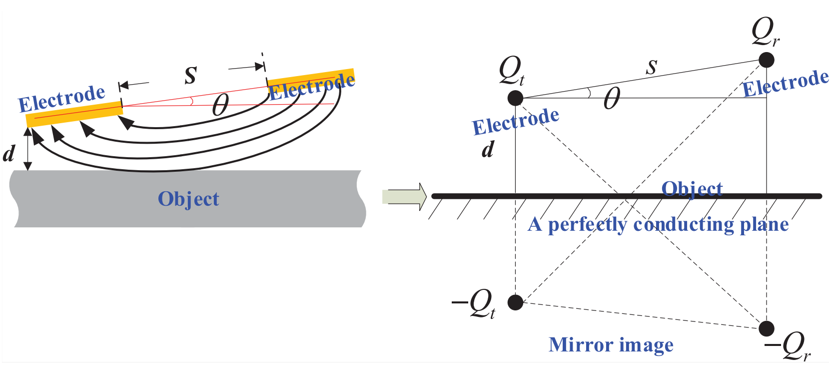



**FIGURE 5.** Mirror charges [31]. When the conducting object is far larger than the electrodes in terms of size, the object can be regarded as a perfectly conducting plane and the two electrodes can be considered two point charges ($Q_t$ and $-Q_t$ represent the transmit electrode and its mirror of the transmit electrode, $Q_r$ and $-Q_r$ represent the receive electrode and the mirror of the receive electrode). Where $d$ denotes the shorter distance between the object and the two electrodes, $s$ represents the electrode gap, and $\theta$ is the angle between the electrode plane and the surface of the object.

into a wider space. A CPS is formed when the fringe field becomes predominant between the electrodes [5]. However, the existing formulations for fringe field often result in complicated mathematical models from which it is difficult to accurately calculate a given CPS [26].

In capacitive displacement sensing modality, as an object approaches a CPS, the relative change in capacitance between a single electrode and ground (self-capacitance as shown in the left side of Figure 4) or between two electrodes (mutual-capacitance as shown in the right side of Figure 4) is measured. In the self-capacitance mode, the object is regarded as a virtual electrode. Therefore, the sensor can be modeled as a parallel capacitor between the electrode and the object. The relationship between the self capacitance and the object distance can be approximately estimated as:

$$C_{self-capacitance} = \frac{\varepsilon_r \varepsilon_0 A}{d}. \quad (1)$$

However, in the mutual-capacitance mode, CPSs are susceptible to the variations in the shape, size, material, and relative position of the objects, thus it is difficult to derive a specific expression with these objective parameters. In general, modeling for CPS is concerned with the simplified features of the objects or the electrodes. For instance, the object is simplified as an infinite plane or the electrodes are regarded as point particles (or point mass). Although many capacitive systems have multiple transmit/receive electrodes, only a pair of transmit and receive electrodes is used for modeling to simplify the models for analysis. There are three methods for modeling of the proximity sensor: the method of images, the method of conformal map, and the method of solution of Laplace's equation. This section introduces these three modelling methods.

### 1) METHOD OF IMAGES

The method of images is a basic mathematical tool in electrostatics, and it is used to visualize the electric field distribution of a charge in the vicinity of a conducting surface [30]. Deng [31] used the method of images to model the target approach process in his doctor's thesis. The modeling process is described below.

When the conducting object is far larger than the electrodes in terms of size, so the object can be regarded as a perfectly conducting plane and the two electrodes can be modeled as two particles, $Q_t$ and $Q_r$, and $Q_t = -Q_r = Q$. The charge distribution is shown in Figure 5. Comparing the electric field without the object, the potentials on the electrodes can be calculated as:

$$\begin{cases} \varphi_t = \Phi_t - \dfrac{Q}{4\pi\varepsilon_0}\left(\dfrac{1}{2d} - \dfrac{1}{\sqrt{4d^2+4ds\sin\theta+s^2}}\right) \\ \varphi_r = \Phi_r + \dfrac{Q}{4\pi\varepsilon_0}\left(\dfrac{1}{2(d+l\sin\theta)} - \dfrac{1}{\sqrt{4d^2+4ds\sin\theta+s^2}}\right), \end{cases} \quad (2)$$

where $d$ denotes the shorter distance between the object and the two electrodes, and $s$ represents the electrode gap, $\theta$ is the angle between the electrode plane and the surface of the object, and $\Phi_t$ and $\Phi_r$ are the potentials on the electrodes without the object.

Further, the variation of potential difference with and without the object can be written and simplified as:

$$\Delta V_{tr} = (\varphi_t - \varphi_r) - V_{tr} \approx \frac{Qs^2}{32\pi\varepsilon_0 d^3}(\sin^2\theta + 1), \quad (3)$$

where $V_{tr}$ is the potential difference without the object.

According to $Q = CV$, equation (3) can be expressed as:

$$\frac{\Delta C_{tr}}{C_{tr}} = \frac{C_{tr}s^2}{32\pi\varepsilon_0 d^3}(\sin^2\theta + 1). \quad (4)$$

where $\Delta C_{tr}$ and $C_{tr}$ are the capacitance variation and the capacitance between the electrodes, respectively.

According to the transformed relationship of mirror charge between conductor and non-conductor [32], (4) becomes:

$$\Delta C_{tr} = \frac{C_{tr}^2 s^2}{32\pi\varepsilon_0 d^3}\frac{\varepsilon_t - \varepsilon_0}{\varepsilon_t + \varepsilon_0}(\sin^2\theta + 1), \quad (5)$$

where $\varepsilon_t$ is the dielectric constant of the object.

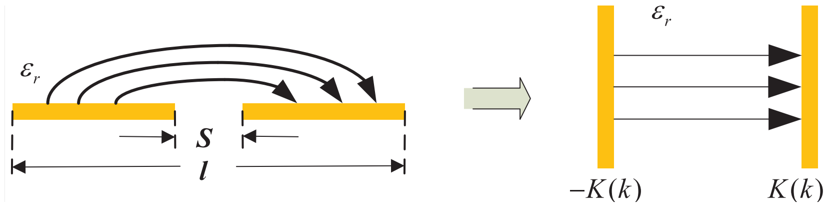



**FIGURE 6. Conformal map technique [34]. (Left) Coplanar structure. (Right) Equivalent parallel structure- result of mapping into a sandwich capacitor without fringing fields. Where $s$ and $l$ are the electrode gap and the sensor length, $K(k)$ is the complete elliptic integral of the first kind, $k$ is the modulus of the eliptic integral, and $\varepsilon_r$ denotes the dielectric constant of the medium.**

Equation (5) shows the relationships between the sensitivity, which is also known as the rate of capacitance change, and the sensor geometry. It is seen that the sensitivity is determined by the sensor geometrical parameters: increasing the electrode gap $s$ or reducing the distance $d$ can result in higher sensitivity, and the object with a higher dielectric constant also can cause higher sensitivity.

### 2) METHOD OF THE CONFORMAL MAP

For a coplanar capacitor, the formula for calculating the capacitance is difficult to obtain. But if we transform the coplanar capacitor to a parallel capacitor and preserve the orientation and angles locally, the calculation will become simple [33]. The conformal map can provide a good way of solving this transformation. The detailed analysis is presented in [34]. As depicted in Figure 6, the electrode gap is $s$ and the sensor length is $l$. The mutual capacitance between the two electrodes is given as:

$$C = \frac{\varepsilon_0\varepsilon_r}{2} \cdot F(k);\ F(k) = \frac{K(k')}{K(k)};\ k = \frac{s}{l};\ k' = \sqrt{1-k^2}, \tag{6}$$

where $k$ represents the modulus of the elliptic integral, and $K(k)$ denotes the complete elliptic integral of the first kind. Further, $F(k)$ can be simplified as:

$$F(k) = \frac{K(k')}{K(k)} = \begin{cases} \pi^{-1}\ln[2\dfrac{1+(1-k^2)^{0.25}}{1-(1-k^2)^{0.25}}] & for\ k^2 \le 0.5 \\ \pi\ln[2\dfrac{1+k^{0.5}}{1-k^{0.5}}] & for\ k^2 \ge 0.5, \end{cases} \tag{7}$$

Equation (7) has a complex form, so Novak et al. in [35] further analyzed and concluded the sensing principle of capacitive sensor. They refined two modes in which the electrodes may be electrically excited: even mode and odd mode [36]. Odd mode is characterized by driving the electrodes with the same time-varying potential, while the odd mode is excited by the signals with a 180° phase shift between them. When the thickness of an infinitely long and flat electrode is much less than the width, the mutual capacitance per unit length may be expressed as the difference between the total even and odd mode capacitances, as written in equations (8)∼(9):

$$C_{\text{mutual}}(s,d) = \frac{1}{2}[C_{\text{odd}}(s,d) - C_{\text{even}}(s,d)], \tag{8}$$

when

$$C_{\text{odd}}(s,d) = \frac{s}{d} - \frac{2}{\pi}\ln[\sinh(\frac{\pi s}{2d})]\varepsilon_0\varepsilon_r, \quad \text{and}$$
$$C_{\text{even}}(s,d) = \frac{s}{d} - \frac{2}{\pi}\ln[\cosh(\frac{\pi s}{2d})]\varepsilon_0\varepsilon_r. \tag{9}$$

For the details on the even and odd mode capacitances, please refer to [35].

For equations (6)∼(8), it can be found that the mutual capacitance effectively increases with reducing the electrode gap $s$ or increasing the sensor length $l$.

### 3) METHOD OF THE SOLUTION OF LAPLACE'S EQUATION

The idea behind this method is that the solution of Laplace's equation gives the electric potential distribution from which the fringe capacitance between electrodes bounding the field can be calculated. Chen and Luo [37] presented a proximity detection model with a ring-shaped sensor which structures with one inner circular and one outer annular electrode are shown in Figure 7(a). The radii of the inner circular and the outer annular electrodes are $R_1$ and $R_2$, the electrode gap is $s$. For the sensing space between the electrode surface and the object surface, and the space-charge density is zero. Thus the solution of Laplace's equation can be written as:

$$\nabla^2 V(x,y,z) = 0, \tag{10}$$

where $V(x,y,z)$ denotes the electric field of the sensing space. The Laplace's equation in the cylindrical coordinate system has the form:

$$\frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\frac{\partial V}{\partial r} + \frac{\partial^2 V}{\partial z^2} = 0, \tag{11}$$

where $r, \varphi, z$ are the three coordinates, respectively. Since the volumes and boundary conditions are axially symmetrical, $V(x,y,z)$ is irrelevant to the coordinate of $\varphi$, and can be written as a sum of products of functions of $r$ and $z$ as:

$$V(r,z) = R(r)Z(z), \tag{12}$$

Substituting equation (12) into equation (13), we can obtain:

$$\begin{cases} \frac{1}{R(r)}\frac{d^2R}{dr^2} + \frac{1}{rR(r)}\frac{dR}{dr} = \eta^2 \\ \frac{1}{Z(r)}\frac{d^2Z}{dz^2} = -\eta^2, \end{cases} \quad (13)$$

where $\eta$ is the eigenvalues of the differential equation (11).

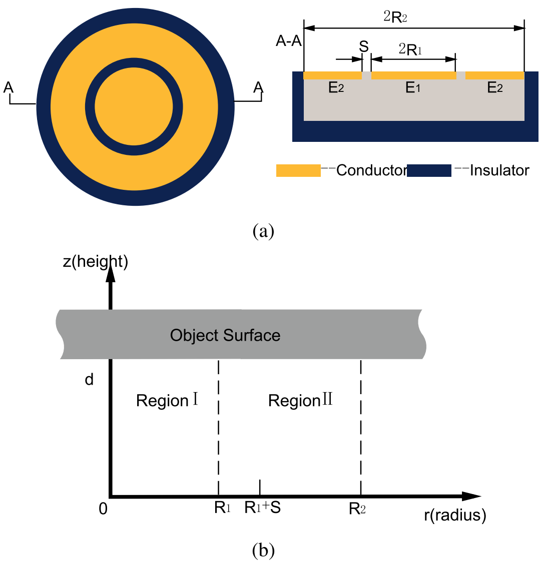



**FIGURE 7. Schematic drawing of the proximity sensor with ring-shaped sensor pattern [37]: (a) Top and cross-sectional view of the sensor. The ring- shaped sensor is comprise of one inner circular and one outer annular electrode separated by an annular insulator. (b) Cross section of the sensor with cylindrical coordinate system. Two regions which specify the boundary conditions are shown: Region I ($R_1 < r < R_1 + s$) and Region II ($R_1 + s < r < R_2$). Where $S$ is the electrode gap, and $R_1$ and $R_2$ are the radii of the inner circular and the outer annular electrodes.**

To obtain a closed-form solution for the sensor model, the boundary conditions with two regions (as shown in Figure 7(b)) are that: Region I ($R_1 < r < R_1 + s$) and Region II ($R_1 + s < r < R_2$). The electric potentials on the surfaces of transmit and receive electrode and the outer surface are $V_0$, 0, and 0, respectively. Thus the electric potentials in the two regions using the properties of the modified Bessel functions can be obtained. Moreover, we know that a capacitance also can be calculated as:

$$C = \frac{\varepsilon_0\varepsilon_r}{V}\iint_A \frac{\partial V(r,z)}{\partial z}|_z dA, \quad (14)$$

According equation (14), the mutual capacitance can be carried out:

$$C_f = 4R_1\varepsilon_0\varepsilon_r\frac{\pi(R_1+S)}{d}\sum_{n=1}^{\infty}\frac{I_1(\frac{n\pi R_1}{d})}{I_1(\frac{n\pi R_2}{d})} \cdot \{I_1(\frac{n\pi R_2}{d})\cdot K_1[\frac{n\pi(R_1+S)}{d}] - K_1(\frac{n\pi R_2)}{d})\}, \quad (15)$$

or

$$C_f = 4R_1\varepsilon_0\varepsilon_r(\rho_1+\rho_s)\sum_{n=1}^{\infty}\frac{I_1(n\rho_1)}{I_1(n\rho_2)}\cdot\{I_1(n\rho_2) \cdot K_1[n(\rho_1+\rho_S)] - I_1[n(\rho_1+\rho_S)]K_1(n\rho_2)\}. \quad (16)$$

where $\rho_1 = \frac{\pi R_1}{d}$, $\rho_2 = \frac{\pi R_2}{d}$, and $\rho_S = \frac{\pi S}{d}$. $I_1(x)$ and $K_1(x)$ are the first-order modified Bessel functions of the first and second kind. $I_1(x) = I_0'(x)$ and $K_1(x) = K_0'(x)$, where

$$I_0(x) = \sum_{k=0}^{\infty}\frac{1}{(k!)^2}(\frac{x}{2})^{2k}$$
$$K_0(x) = -(\ln\frac{x}{2}+\gamma)I_0(x) + \sum_{k=0}^{\infty}\frac{1}{(k!)^2}(\frac{x}{2})^{2k}\sum_{l=1}^{k}\frac{1}{l} \quad (17)$$

More details of the derivation processes can be found in References [37], [38].

For equation (17), it is difficult to directly observe the change the regularity of the mutual capacitance with the sensor geometrical parameters, but can be obtained the conclusions by analysis the properties of the modified Bessel functions.

The three methods for modeling capacitive displacement sensing have their unique features: The method of images with a concise deduction reveals an association with the sensor sensitivity and the sensor geometrical parameters, however it ignores the impact of the electrodes' size. The method of the conformal map is suitable for modeling proximity sensors with any electrode shape, but the calculation is complicated. Although the sensing model using the method of solution of Laplace's equation has a closed-form solution only when the sensor shape is a ring, drawing on the strength of the processing power of computers can be simulated the sensor with any electrode shape based on this method.

Despite the fact that these theoretical analyzes are produced with some idealized assumptions and strict boundary conditions, and the responses on capacitance cannot be precisely expressed due to a variety of affected factors (e.g. the parasitic effects for the environment), these modeling methods can help readers to fully understand the principle of capacitive displacement sensing from three different ways, and also can provide a guideline for parameter optimization of sensor during design process.

## III. APPLICATIONS

CPSs in displacement sensing modality are able to measure position and displacement with high accuracies. Besides measuring displacement/distance, capacitive displacement sensing is also being intended for measurements of physical quantities, like pressure, speed, acceleration, angle, vibration, even interactive intents. These applications belong to the category which they rely on the same principle: sensing the change in the position of objects. CPSs offers an effective, less expensive and reliable alternative since they are inexpensive, robust, flexible and easy to manufacture [39].

The applications of capacitive displacement sensing can be divided into two main categories according to whether the measured physical quantity is directly measured or not: displacement/distance measurements (direct measurements) and indirect measurements. Also, with the rising development of the applications in smart environments, we especially group

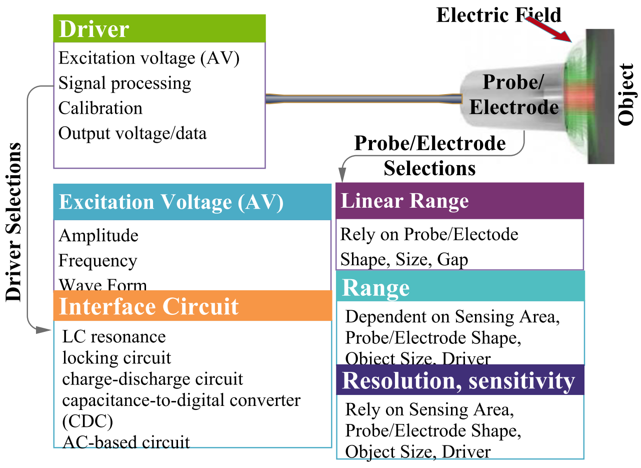



**FIGURE 8.** Capacitive displacement/distance sensor system.

the relative applications into one category. In this section, we will review the state of the art applications in these three categories successively.

### A. CAPACITIVE DISPLACEMENT SENSING FOR DISPLACEMENT/DISTANCE MEASUREMENTS

Capacitive displacement/distance sensors use the electrical property of ''capacitance'' to make displacement or distance measurements and have been widely used in several industries applications for many decades. Figure 8 shows how a capacitive sensor works for displacement or distance measurement, and also reveals the performance parameters and the respective conditions on which they depend. For instance, the linear range relies on probe/electrode shape, size as well as electrode gap [5], [40], [41]; detection range dependents on sensing area, probe/electrode shape, target size, and driver as well; resolution and sensitivity rely on the same conditions as detection range [3]–[5], [40], [41]. Note that the driver includes excitation form (i.e. amplitude, frequency and waveform of excitation signal) and interface circuit (e.g. LC resonance locking circuit [43], charge-discharge circuit [44], capacitance-to-digital converter (CDC) [45], AC-based circuit [46], etc.). Several reviews [3]–[5] of CPS concluded the sensor features. We will review the milestone detectors which are applied in novel applications or used with novel detection approaches.

CPSs can be used not only as linear displacement meters but also as distance detectors for non-precision tasks.

#### 1) LINEAR DISPLACEMENT MEASUREMENTS IN PRECISION APPLICATIONS

A CPSs can detect objects with a high distance accuracy in a small range because there is an approximated linear region near the origin in capacitance measurement [37]. Noltingk [48] firstly introduced CPSs and demonstrated the linear range varies with electrode gap. Smith *et al.* [49] used finite element analysis (FEA) to successfully predict corrected sensitivities and nonlinear residuals for spherical targets. Vallance *et al.* [50] introduced means of parametric numerical calculations based on FEA to modify one of the presented models with a polynomial correcting factor to obtain a better accurate estimation of the sensing capacitance. Addabbo *et al.* [24] extended the study for CPS design and provided a comparison of the three-electrode shape, i.e. Ring-shaped, rectangular and multi-electrodes. The experiments concluded that the ring-shaped sensor and the rectangular sensor are better than the multi-electrode sensor in terms of linear range. A typical commercial capacitive displacement sensor product commonly employs the self-capacitance mode: a sensing electrode and guard ring enclosed within a grounded sensor body. High-performance commercial displacement sensor products use small sensing surfaces to detect the targets positioned close to them and have typical sensing ranges from 0.05 to 20 mm. A summary of the detailed operation principle and error analysis performed in [6] is contained in Section 3.4.

Non-contact capacitive gap/clearance sensors have been used in the gap/clearance measurements which are essentially the detection of the relative linear displacement between two components. These gaps or clearances are generally found in a wide variety of applications from attaching wings to aircraft and measuring the blade tip clearance of turbine engines to detecting gaps in the processes of metallurgy, coating, extrusion and laminating composite materials [56]–[61]. Optimum running clearance ensures safe engine operation and better specific fuel consumption indirectly [56]. However, hostile work environment, poor performance and high costs make several measurement methods impossible to apply. Capacitive sensor systems are perfectly satisfactory to the requirements of these tasks because the capacitive sensors are small, simple, and have high detection capability. In [56]–[61], some capacitive gap/clearance sensors with different accuracies are proposed. Table 1 lists various well-characterized and reported linear displacement sensors.

#### 2) LONG-DISTANCE MEASUREMENTS IN NON-PRECISION APPLICATIONS

When the object is measured at a large distance, the capacitive sensor's output is probably nonlinear with the object distance that results in increasing measurement errors. Despite the nonlinearity in capacitive distance measurements, it is important but not critical in non-precision applications. Capacitive sensing offers many advantages (e.g. insensitive to lighting, audible noise, the colour, surface and texture of the object), and allows a relatively large area of coverage, that makes it suitable for use in industrial contactless object detections.

Robot tactile and proximity sensors, the successful applications of capacitive sensing, are the devices to acquire proximity information of objects or obstacles for preventing from any possible accidental collisions or achieving a series of grasping actions [63]–[66]. In general, a dual-mode capacitive sensor consisted of two electrode layers is employed to implement the tactile and proximity capability: the top layer is utilized as proximity sensor while the top and bottom layers

**TABLE 1. Summary of Capacitive linear displacement sensors.**

| Work | Description | Size and shape | Resolution | Linearity/Error | Linear range | Measuring range |
|---|---|---|---|---|---|---|
| [52] | In-line/Pillar design: five/six pillar probes | $\phi$ 3-7.6 mm | 0.2 $\mu$m | 0.5/0.1 aF/$(\mu m)^2$ | 1.95 $\pm$0.5 mm | 0.4-3 $\mu$m |
| [53] | Commercial capacitive displacement products | $\phi$ 0.3 -21 mm | 0.0007%-0.03% | 0.2%-0.5% | 0.05-12.5 mm | $\sim$20 mm |
| [54] | Combined vertical and horizontal-comb shape | 200 $\times$ 850$\mu m$ | 0.1 nm | - | 1.3-3.6 $\mu$m | - |
| [55] | Pillar probe | $\phi$ 10mm | 0.1 $\mu$m | Error: $\pm$80 pm | - | 10 $\mu$m |
| [57] | To measure the blade-tip gaps | $\phi$ 7.6 mm | 10 $\mu$m | Error: 0.8-97.6 $\mu$m | $\sim$0.75 mm | 0.4-3 mm |

[1] $\phi$** represents the diameter of the electrode is **

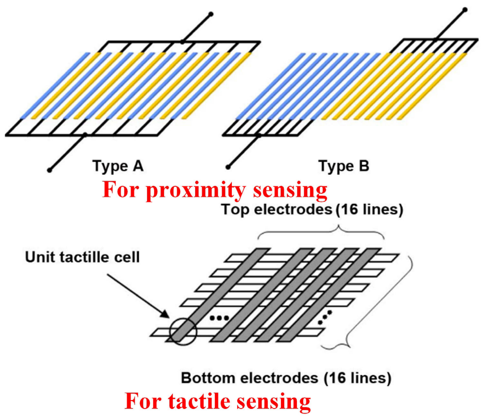



**FIGURE 9. Capacitive proximity and tactile sensor [63], [64].**

form a tactile sensor with capacitive deformation sensing as shown in Figure 9. In [67], the tactile sensing is implemented by pressing the cover upon the surface of the sensor when a normal force is applied to it.

These researches mainly focused on object detections in vertical direction. Some other studies proposed prototypes of CPS for displacement measurements in other directions. In [68], a coplanar capacitive sensor is employed to measure horizontal displacement. In [27], four capacitive sensing elements are assembled on the four sides of a cube that is used to detect the proximity of objects at different positions and directions. To decrease the crosstalk, each capacitive sensing structure is connected to an inductive element to form resonance at different frequencies. In [69], Lü et al. proposed a novel co-planar sensor which consisted of a circular driving electrode, and four sensing electrodes around the driving electrode. The four sensing electrodes are symmetrically distributed and used to identify direction of the approaching object. In [70], Ye et al. utilized a large-scale capacitive sensors to detect the small high-speed ( whose speeds exceed 1000 m/s) moving targets from different directions. Unlike the previous applications, the surface area of the sensor is much greater than that of the target so that the measured distance is affected by the sensitivity distribution of a single sensor. They compared the sensitivity distribution homogeneity of four electrode shapes, and concluded that the spiral and comb shape have better performance on sensitivity distribution homogeneity than the circular and rectangular shape.

In addition, others [66], [71]–[73] realized a multi-sensor fusion scheme to make up for each sensor's disadvantages. Capacitive sensors are sensitive to both metallic and dielectric (non-metallic) objects and lack of detection distance. Thus, they combined with some different sensor techniques (e.g. camera video sensor [71], temperature sensor [66], inductive sensor [72], [73], ultrasonic sensor [74], and so on), that is capable of optimizing the probability of discrimination between metallic and dielectric objects (combined with camera video sensor and inductive sensor), and improving the detection range (combined with temperature sensor and ultrasonic sensor).

These aforementioned approaches for object distance measurements have used conventional data analysis methods, which are data fitting. However, there are some drawbacks to conventional measurement methods based on data fitting approach. Firstly, owing to nonlinearity relationship between capacitance change and object distance, the measurements are carried out with large errors, especially in the nonlinearity range of the CPS. Secondly, conventional methods can only obtain high measurement accuracy when measuring a target in a specified direction. Thirdly, existing conventional methods mainly focus on the distance measurements for given targets, not for unknown targets.

In [75], a 4 $\times$ 4 electrode matrix yielding 16 independent electrodes is used to improve the spatial resolution. Three configurations are employed to measure the vertical distance and track the parallel motion. As shown in Figure 10, the three configurations are that: Type I represents a comb electrode structure, Type II is grouped into two equal halves, and Type III utilizes only the two most remote electrode strips as transmitter and receiver. Quantitative regression models are built to detect an object with a resolution of 3 cm.

Recently, machine/deep learning tends to overcome those downsides. Ziraknejad *et al.* [76] first introduced a BP feed-forward neural network approach using Levenberg-Marquardt algorithm to measure vehicle occupant's head position for self-contained autonomous and adaptive head restraint positioning system (as shown in Figure 11). A three-sensor configuration applied in the measurement system is set in a form of an inverted "Y" with equal angular orientations

$$TypeI:\begin{bmatrix} T & R & T & R \\ T & R & T & R \\ T & R & T & R \\ T & R & T & R \end{bmatrix} \quad TypeII:\begin{bmatrix} T & T & R & R \\ T & T & R & R \\ T & T & R & R \\ T & T & R & R \end{bmatrix}$$

$$TypeIII:\begin{bmatrix} T & G & G & R \\ T & G & G & R \\ T & G & G & R \\ T & G & G & R \end{bmatrix}$$

**FIGURE 10. Three configurations for distance measurement [75]. "T": transmitter; "R": Receiver; "G": Grounded. The same letters represent the electrodes connected together.**

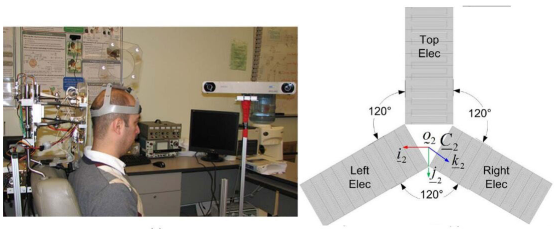



**FIGURE 11. CPS for measurement of vehicle occupant's head position [76]. (Left) Data collection experimental test bed. (Right) Front view of the coordinate system assignment for the Y-shaped sensor arrangement.**

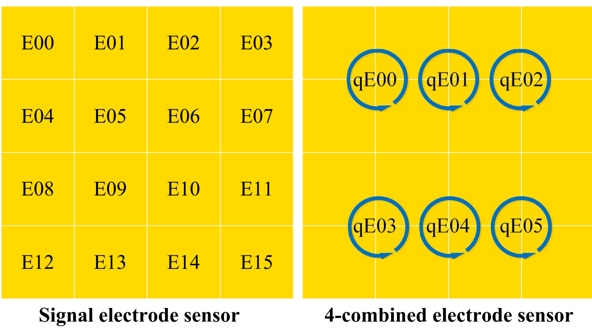



**FIGURE 12. The two class capacitors in [77]: (Left) single electrode sensors (E00-E15) and (Right) 4-combined electrode sensors (qE00-qE05, four adjacent electrodes make up a large electrode.).**

of 120°. The three independent capacitive proximity ratios $(c_1, c_2, c_3)$ with time $t$ are used to form the input variable vector $C_t = [C_{1t}\ C_{2t}\ C_{3t}]^T$ while the measured occupant's head coordinates $X_t = [x_t\ \ y_t\ \ z_t]^T$ are used to form the output variable vector of the network with two hidden layers. This neural network approach offers high accuracy and can estimate the 3-D head position in real-time with a mean Euclidean distance error of 0.33 cm.

Hein *et al.* [77] proposed another machine learning approach: the distance classification artificial neural network (ANN) with 3 hidden layers for evaluating distance measurements. Two sensor modules with $2 \times 8$ electrodes are used as sensing elements. The two-class capacitors, single electrode sensors (E00-E16) and 4-combined electrode sensors (qE00-qE05), are fed to the neuronal work. The experiment results show the distances close to the sensor can be distinguished quite good, but far distances led to misclassifications.

These machine learning approaches are relatively accurate for given targets in any positions in the sensing area, but the relative researches for unknown targets, the third downside of conventional measurement methods, have not yet been reported.

### B. CAPACITIVE DISPLACEMENT SENSING FOR INDIRECT MEASUREMENTS

In addition to displacement/distance measurements, capacitive displacement sensing can be used in indirect measurements. More specifically, we can employ the position information of objects to measure other physical quantities, like force, pressure, title, speed, angle, and so on.

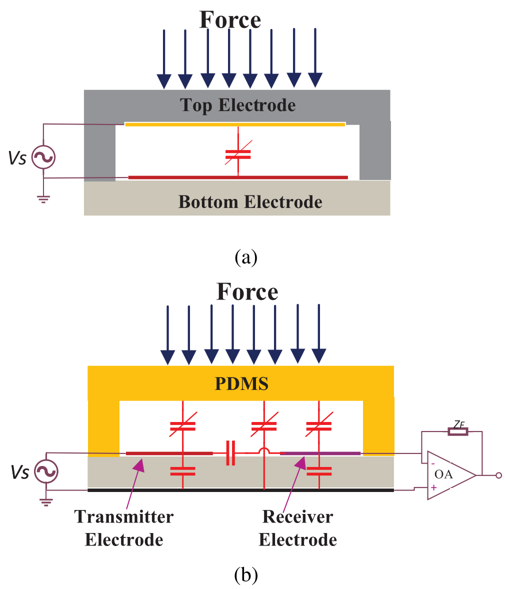



**FIGURE 13. Capacitive force sensor based on (a) deformation sensing, and (b) displacement sensing.**

CPSs can detect external deformations occurred on targets, and they are developed to perceive external pressure or force. As shown in Figure 13, when an object is applying force to the deformable layer, decreasing the distance by deforming the deformable layer that results in a higher sensor value. There are two testing modes: deformation sensing and displacement sensing. Compared with the two testing modes, the former offers a higher sensitivity, and the latter is simpler to implement in structure design and electrical connection. Besides, for the displacement sensing, the measurement results are affected by the dielectric membrane properties, which include thickness, material and geometry. In practical applications, the capacitive pressure/force sensor is implemented on Printed Circuit Board (PCB) or Flexible Printed Circuit Board (FPCB) substrate and covered with conductive fabric [79] or polyimide or elastomeric material [80], [81] which is as deformation layer. Normally, to obtain a high sensitivity, good resolution and linear response, the deformation layer is assembled in the linear range of CPS. The sensitivity of the capacitive pressure/force sensor is also impacted by the elastic coefficient of the deformation layer.

**TABLE 2.** Summary of Capacitive distance sensors.

| Work | Description | Size and shape | Measuring range | Error/Resolution | Shielding mode | Measuring method |
|---|---|---|---|---|---|---|
| [63] | Printed on a standard polyester woven fabric | Spiral:18 × 18 cm, thickness:30 $\mu$m | 8 cm | Resolution: 0.05 cm | No Shielding | CDC: MTCH112 |
| [64] | Two layers of 16×16 electrode arrays | Single sensor: 10 cm× 5 mm | 17 cm for hand | - | Active shielding | Charge amplifier circuit at 250 kHz |
| [67] | Dual-mode: integrated capacitive and temperature type sensor | 0.7 cm× 0.3 cm, Gap=0.1 mm | 1.7 cm for plastic block | - | Active shielding | CDC: AD7746 |
| [70] | Circular-shape driving electrode, four sensing electrodes symmetrically distributed | 4.5 cm × 4.5 cm | 5.5 cm, direction recognition | 0.40%-4.57% | Ground shielding | LCR |
| [71] | CPS for moving target (more then 1000 m/s) detection | 31 cm × 19 cm | 60 cm | Error: 5 cm | Ground shielding | C/V circuit and LPF |
| [73] | Combined capacitive and inductive sensor | Sigle Electrode: 2 cm × 0.5 cm | 1 cm | - | - | LC resonance |
| [75] | Combined capacitive and Ultrasonic | Sigle Electrode: 6 cm × 3 cm, thickness: 0.1 mm, gap: 5 cm | Total range: 200 cm | - | Ground sheilding | CDC: AD7143 |
| [76] | Arrayed 4×4 | Signal sensor: 1 cm× 1 cm, gap: 0.5 cm, Array: 6.5 cm× 6.5 cm | 18 cm | Resolution: 3 cm | Active shielding | CDC: AD7746 |
| [77] | Three sensors with equal angular coordinates of 120°. | Signal sensor: 8.55 cm× 4 cm | 33.68 cm | Resolution: 0.33 cm | Ground shielding | Data process method: BP neural network |

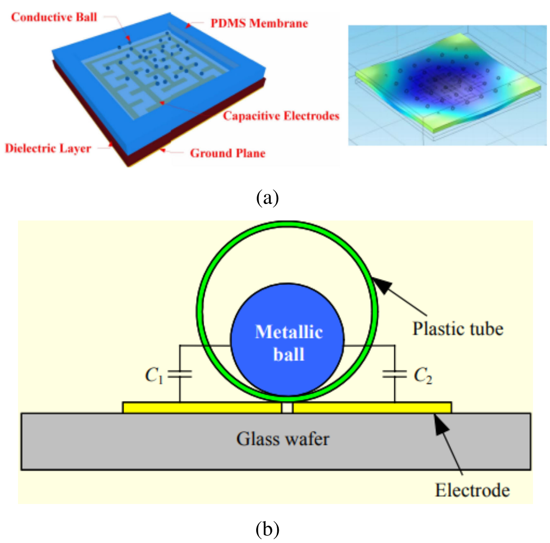



**FIGURE 14.** Capacitive tilt sensors. (a) The sensor covered with a PDMS (polydimethlysiloxane) membrane can perceive the tilt angle, which is caused by the pressure from the conductive balls upon the PDMS membrane [82]. (b) A metallic ball is placed in a plastic tube which is fixed on a capacitive sensor, and the tilt angle can be determined by the analysis from the capacitive variance trends and the capacitance variations [83].

With similar measurement method of capacitive force sensor mentioned above, Karuthedath and Schwesinger [82] used a capacitive sensor to perceive the tilt angle of the polydimethylsiloxane (PDMS) membrane (as shown in Figure 14(a)). Lee et al. [83] proposed another tilt angle measurement approach (as shown in Figure 14(b)). A metallic ball is placed in a plastic tube which is fixed on a capacitive sensor. With the metallic ball rolls in the plastic tube, the capacitances $C_1$, $C_2$ ($C_1$ is the capacitance between the left electrode and the metallic ball, and $C_2$ is the capacitance between the left electrode and the metallic ball) vary with the distances between the electrodes and metallic ball changes. But the capacitance variations move in opposite directions, i.e. as one increases the other decreases. Thus, the tilt angle can be determined by the analysis from the capacitive variance trends and the capacitance variations.

In [84]–[86], segment cylindrical capacitive sensors are used to measure the radial and axial error motion of rotating machinery. In [87], capacitive probes are used to measure the aspheric surface.

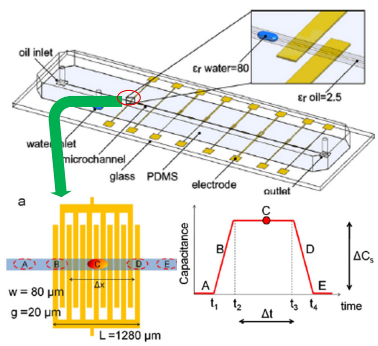



**FIGURE 15.** CPS for detection of microdroplet size and speed [88].

In [88], a CPS with interdigital fingers is used for detection of microdroplet size and speed (as shown in Figure 15). When a droplet enters the sensing region the capacitance signal increases, and then quickly saturates as it is completely in the sensing region for a time $\triangle t$ until it leaves. The saturation signal strength, $\triangle C_s$, is used to measure the size of the droplet, while the saturation time is employed to calculate the speed of the droplet using the formula $v = \triangle x / \triangle t$.

Anandan and George [89] utilized a new sensor to measure both linear and angular displacements. Two fixed pairs of semi-hollow cylinder electrodes surround a cylindrical shaft, which is free to move along its axis or rotate about its axis.

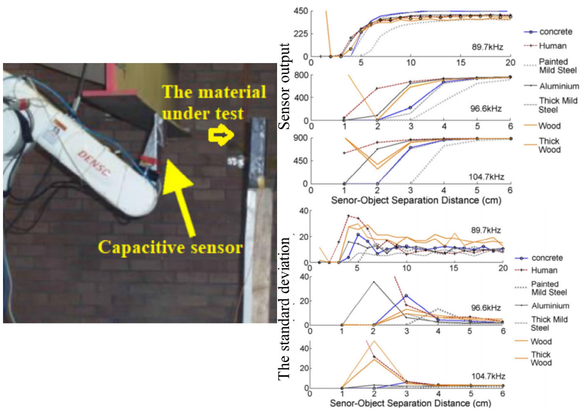



**FIGURE 16. CPS for material type identification based on the deviations varied with object distances in the readings taken at different sensor drive frequencies [90].**

In these applications, there is an exact function between the distance changes and the measured parameters. Another side applications of indirect measurement technique regards measurements based on object distance features. Kirchner *et al.* [90] presented a capacitive displacement sensing system for material type identifications (as shown in Figure 16). The material type of planar patches are classified by the deviations varied with object distances in the readings taken at different sensor drive frequencies based on a supervised learning scheme. In this work, the obtained average classification accuracy is approximately 94% in clear air and reduced 6% in air heavily laden with particles. Osadcuks and Pecka [91] also used capacitive proximity sensing method to recognize fruit or vegetable. In [75], a $4 \times 4$ electrode array is configured to eight sensing capacitances. These capacitance values are grouped into eight-dimensional input vectors of a support vector machine for profile recognition. Combined with machine/deep learning approaches, conceived sensor systems based on object distance features will be more widely employed for indirect measurements. Table 3 lists various parameters using capacitive displacement sensing.

**TABLE 3. Summary of Capacitive displacement sensing for indirect measurements.**

| Physical quantities | Work |
|---|---|
| Force/Pressure | [80]–[82] |
| Tilt angle | [83], [84] |
| Radial and axial error | [85]–[87] |
| Aspheric surface | [88] |
| Speed | [89] |
| Angular displacement | [90] |
| Material identification | [91], [92] |
| Surface profile recognition | [76] |

### C. CAPACITIVE DISPLACEMENT SENSING IN SMART ENVIRONMENTS

The idea to build a smart environment with embedded smart devices that make the room perceive physical state and activities within. In a smart environment, user routines and information processes may seamlessly interact with each other that lets inhabitants' lives more comfortable [92]. CPSs can be unobtrusively applied, or even provide information when hidden from sight [1]. In the past years, various research groups have been using this sensor category to create singular applications in this domain. Figure 17 depicts how capacitive sensing system works for human interaction in smart environments. A physical world interwoven with sensors, actuators, and computational elements and etc, embedded seamlessly in our daily lives that creates a smart environment. Interactive devices are seamlessly embedded with CPSs capable of sensing distance, orientation, movement, identity, trajectory, and location. Data processing part (computational elements) is a unit that achieve data acquisition and processing. The realization process is as follows:

First, the CPSs capture the disturbance of the electric field caused by human body (e.g. hand, foot, eye, and etc.), and then the raw signals of the CPSs are measured by measuring circuit. Second, the signals involved with the interactive information (e.g. distance, orientation, movement, identity, trajectory, and location) are processed using signal processing approaches and/or machine/deep learning approaches (e.g. Hidden Markov Model(HMM), Dynamic Time Warping (DTW), Supper Vector Machine (SVM), Convolutional Neural Network (CNN), and so on). At last, the human actives are monitored or the interactive responses associated with the human interactive intentions are activated. Note that the capacitance changes caused by object distance change or the distance features of the measured object both can be utilized to accomplish preset tasks in these applications.

On the following pages, we will give a detailed overview of the applications of CPSs in smart environments, and establish a classification in comparison to several existing publications.

#### 1) GESTURE RECOGNITION AND POSTURE TRACKING

Capacitive touchscreens are ubiquitous input devices of gesture sensing for human-computer interaction, and they are usually performed by applying a matrix of rows and columns of conductive material. A voltage is applied to the rows or columns, and the touch location can be determined by accurately measuring the voltage in the other axis at each individual point on the grid. Somewhat differently, the row-column type of electrode fabrication is difficulty employed in CPS systems for long-distance sensing. In early gesture recognition systems, some simple interactive forms (e.g., motion [93], approach [94], [95], swiping [96], [97]) are exhibited.

Extending the perceptional capabilities of capacitive interactive technology, recent works have been focused on more complex interactive ways.

Tracking the hand position can be obtained motion trajectories, then 2D gesture graphs are performed to interact. A $n \times m$ electrode array is usually used as the sensing component, and the hand position in xy-coordinates can be calculated by a linear weighted summation of sensor

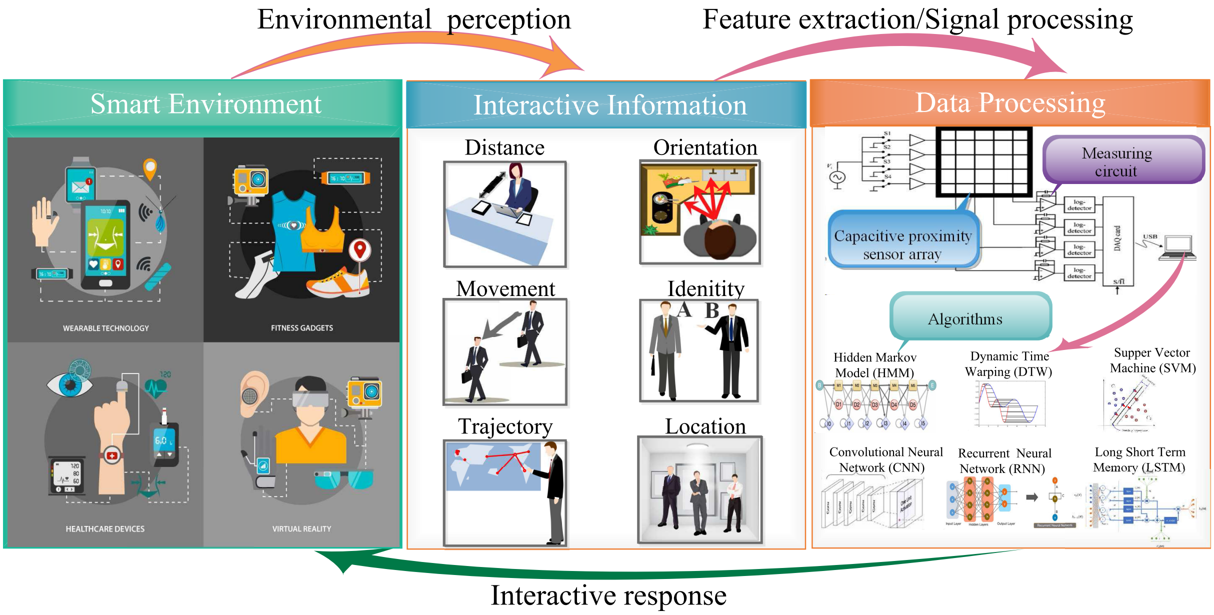



**FIGURE 17.** An illustration of a smart environment based on CPSs.

positions for any number of sensors ($N$), multiplied by their capacitance ($c$) [98]–[100]:

$$\begin{cases} \widehat{x} = \sum_{i=1}^{N} c_i x_i / \sum_{i=1}^{N} c_i \\ \widehat{y} = \sum_{i=1}^{N} c_i y_i / \sum_{i=1}^{N} c_i . \end{cases} \tag{18}$$

Ye *et al.* [101] used $\Delta c$ to replace $c$ in the above equation for eliminating the calculation error caused by the influence of electrode position, which can lead to the differences among the initial capacitances. Nelson *et al.* [99], [100] proposed the two gesture recognition algorithms, DTW and an algorithm combined with HMM and DTW, to recognize the EdgeWrite gestures which are alphanumeric gestures. Endres *et al.* [102] used DTW for recognition of 2D Microgestures for drivers.

3D gesture interaction is added the information of z position to improve users' interaction experiences. Some simple gesture interactions were explored in existing works, e.g. multi-hand zoom and rotation gestures or hand grasping [103]–[107], push or pull [108].

Except for hands, a human can interact with other sensory ways, like eyes, feet or other parts of the body. Rantanen *et al.* [109], [110] utilized a CPS to detect frowning and lifting eyebrows for gaze tracking. Frank and Kuijper [111], [112] used a four-electrode CPS system to distinguish four feet gestures, i.e. heel rotation, heel tap, toe tap and toe rotation.

Also, gestures not only can be recognized through the motion trajectories, but also can be classified using the capacitive signals caused by the user's actions. Chu *et al.* [113]–[116] and Chu and Yang [117] presented four recognition algorithms based neural network, i.e. adaptive fuzzy neural network (AFNN), recursive sine cosine base function neural network (RSCNN), recursive back propagation neural network (RBPNN), and recursive Chebyshev neural network (RCNN), to recognize the gesture signals based on CPSs. In [118], M. Oliveira et al. analyzed the signals detected from the two pair of capacitive sensors in time and frequency domains to recognize four motor activities of the hand and wrist (i.e., radial and ulnar deviation, flexion and extension). Braun *et al.* [119] presented a new method for gesture recognition. They used the geometric positions of the sensors and the capacitance values for a period of time to generate a frame of the capacitive image, and then utilized a SVM to classify the gesture performed by these consecutive images.

Posture tracking plays a role in human activity supervision or posture adjustment. Capacitive systems for posture tracking, which mainly capture static postures, are different from that for gesture recognition. In [120], wall embedded with a CPS with large size is used to detect the postures of standing and fully crouching. In [1], [112], [121]–[124], the whole-body movements and postures are recognized by capacitive proximity sensing equipped on furniture such as couch and bed. In [76], [125], capacitive proximity sensing is constructed for Advanced Driver Assistance Systems (ADAS) for identifying the occupant posture and tracking the motion of occupant. They were respectively used neural networks and deep learning networks to train sensor position data to achieve higher accuracies of occupant position classification.

Based on the above analysis, we conclude the existing interactive scenarios of smart environments using CPSs as shown in Figure 18: using different body parts to interact with the physical world through different actions.

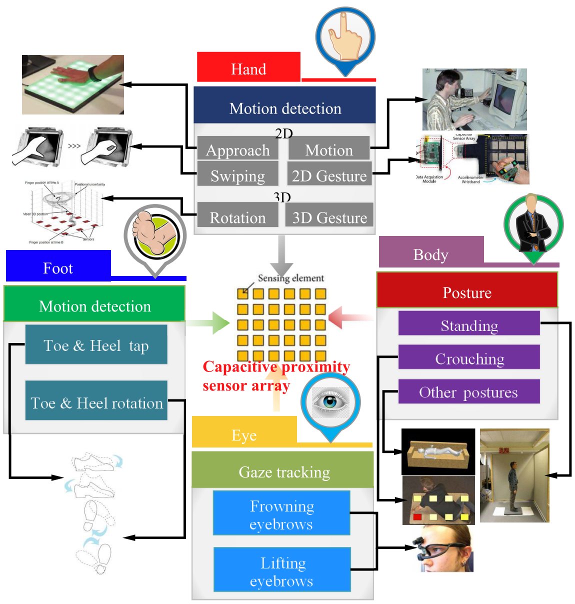



**FIGURE 18.** Using different body parts to interact with the physical world through different actions.

### 2) INDOOR LOCALIZATION

Indoor localization is an important technology to be used to locate objects or people inside a building. It is usually required to identify the approximate position of the objects without a high resolution in the environment, and offers some information, including position, moving direction and speed. Capacitive sensing approaches for indoor localization commonly involve placing several electrodes in self-capacitance mode [126]–[129] or embedding crisscross electrodes in mutual-capacitance mode [130]–[137].

In self-capacitance mode: Iqbal *et al.* [126] used a large electrode (16 cm× 16 cm) to achieve a high detection distance (sensing up to 2 m). In [127], electrical wires, existing powerlines in house are used as the transmit nodes in order to reduce the electronics. Tariq *et al.* [128] and Akhmareh *et al.* [129] proposed a tagless indoor person localization system. Four electrodes are positioned at the center of each one of the four "walls" of the room, and 16 labelled positions are estimated by the signals of the four sensors using Machine learning (ML) classifiers. The results show ML classifiers can effectively reduce the electrode number, and mitigate sensor data variability and noise resulting from the effect of the environment.

In mutual-capacitance mode: crisscross electrodes are typically installed underneath floor [130]–[134] or attached to the walls [135]–[137], and the positions of the user are locked by the electrode whether the user is standing on or facing to.

### 3) USER IDENTIFICATION

Human body is unusual concerning their dielectric properties to the surrounding things and, moreover, the dielectric properties differ from each other with age, wight and hight. Capacitive sensing, therefore, can exploit the dielectric properties for user identification. Pottier *et al.* [138], [139] used the capacitance and the sensitivity variations varied with distance to discriminate between human being and metallic objects. Grosse-Puppendahl [134] used capacitance changes varied with different persons when walking for identification. Roukhami *et al.* [140] and Iqbal *et al.* [141] proposed a tagless remote human identification system based on signatures of capacitance variation with frequency for each person to identify different persons. In this method, a multilayer perceptron neural network is used to train the abstract signatures of persons. In [130], [137], indoor human identifications are constructed by footstep detection based on capacitive sensor array.

## IV. CHALLENGES AND POTENTIAL APPROACHES

Although CPSs are rapidly growing in the last decade due to their desirable properties, some challenges still need to be faced. The following challenges and potential approaches to program implementation are discussed:

(1) **Lack of interaction distance:** The detection range of a CPS strongly depends on the electrode size, thus the electrodes need a certain size to enable detection at a large distance. Lack of interaction distance may limit/restrict the sensors' utilization. The conventional approaches for enhancing the detection range are increasing the electrode size or improving the performance of the interface circuit, but these efforts have limited effects. What's more, there is a trade-off of resolution and detection range in a sensor array system. Current researches provide promising references, such as combined with another detection techniques (e.g. inductance sensor, ultrasonic) or fusion of multi detection techniques (e.g capacitive micromachined ultrasonic transducer (CMUT) [142]). In addition, in [75], determinant sensing configurations are used to perceive targets to replace the usage of a pair of electrodes in a sensor array system. This approach can obtain a high resolution and good detection range. Meanwhile, it requires a faster response time of the capacitance measuring circuit to meet real-time performance requirement because the working electrodes are needed to switch several times in one period of measurement.

(2) **Imperfect measurement accuracy in the nonlinear range:** Perhaps the most criticized problem is imperfect measurement accuracy in the nonlinear range of the sensor, especially for an unknown target. A method which combines a big sample data and machine/deep learning approaches shows a huge potential to address this issue [76], [77].

(3) **Interaction or location space is limited:** For applications of gesture recognition and localization, the effective results can be carried out when the objects or human beings only moving in the vertical sensing space within the boundaries of the electrode array. However, when the motions exterior the vertical sensing space, it doesn't work using the existing approaches. Solving this problem can enlarge the interactive space so that capacitive sensing applications become more practical and feasible.

(4) **Disturbance from surroundings:** Capacitive sensors are susceptible to the surround environments (changes of environmental conditions, e.g. temperature, humidity, lighting; or changes of indoor objects, e.g. presence, position.) that can adversely affect sensor data accuracy. Based on machine learning classifiers or other machine/deep learning methods, the post-processing for raw sensor data rather than the converted discrete distance can effectively mitigate sensor data variability and noise due to deployment-specific environmental conditions [111], [128].

Therefore, many efforts are needed to address these key issues and questions. As for future research, we confirm that object distance features combined with machine/deep learning approaches that is one of the most promising and leading technologies.

## V. CONCLUSION

In this review, we presented the state-of-the-art of the role of CPSs working in displacement sensing modality. CPSs are simple, low cost and very energy-saving, and can be equipped under any nonconductive covering. Capacitive displacement sensing works for long distance and is able to measure more physical quantities compared with capacitive volume and deformation sensing. In fact, Capacitive displacement sensing has been used in displacement and position monitoring applications. In the most recent years, the applications based on capacitive displacement sensing have been greatly emerging in indirect measurements, especially devoted to smart environments. These applications depend on ingenious structural designs of detectors or object distance features to obtain more measurement information. There is a need to characterize and classify these applications. That is the aim of this paper, thus covering the most relevant literature concerning approaches to the applications of CPSs. Another purpose of this paper is to inspire more researchers and developers to find wide applications perspectives.

In the future, it is possible to develop research opportunities of CPSs in object identification and human interaction. Especially, as they are not involved users privacy and have desirable properties, the usage of capacitive displacement sensing in smart environments can not be omitted and has much future scope. Meanwhile, capacitive technique has to face several challenges, including short detection distance, imperfect measurement accuracy, small interaction & location space limited to the boundaries of the electrode array, and disturbance from surroundings, that continues to need new breakthroughs and innovations.

## REFERENCES

[1] A. Braun, R. Wichert, A. Kuijper, and D. W. Fellner, "Capacitive proximity sensing in smart environments," *J. Ambient Intell. Smart Environ.*, vol. 7, no. 4, pp. 483–510, Jul. 2015.

[2] L. Peng, J. Ye, G. Lu, and W. Yang, "Evaluation of effect of number of electrodes in ECT sensors on image quality," *IEEE Sensors J.*, pp. 1554–1565, May 2011.

[3] X. B. Li, S. D. Larson, A. S. Zyuzin, and A. V. Mamishev, "Design of multichannel fringing electric field sensors for imaging. Part I. General design principles," in *Proc. Conf. Rec. IEEE Int. Symp. Electr. Insul.*, Sep. 2004, pp. 406–409.

[4] X. B. Li, C. Kato, A. S. Zyuzin, and A. V. Mamishev, "Design of multichannel fringing electric field sensors for imaging. Part II. Numerical examples," in *Proc. Conf. Rec. IEEE Int. Symp. Elect. Insul.*, Sep. 2004, pp. 410–413.

[5] X. Hu and W. Yang, "Planar capacitive sensors-designs and applications," *Sens. Rev.*, vol. 30, no. 1, pp. 24–39, 2010.

[6] A. J. Fleming, "A review of nanometer resolution position sensors: Operation and performance," *Sens. Actuators A, Phys.*, vol. 190, pp. 106–126, Feb. 2013.

[7] B. George, Z. Tan, and S. Nihtianov, "Advances in capacitive, eddy current, and magnetic displacement sensors and corresponding interfaces," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9595–9607, Dec. 2017.

[8] T. Grosse-Puppendahl, C. Holz, G. Cohn, R. Wimmer, O. Bechtold, S. Hodges, and J. R. Smith, "Finding common ground: A survey of capacitive sensing in human-computer interaction," in *Proc. Conf. Hum. Factors Comput. Syst. (ACM CHI),* May 2017, pp. 3293–3315.

[9] T. Sivayogan, "Design and development of a contactless planar capacitive sensor," M.S. thesis, Univ. Toronto, Toronto, ON, Canada, 2013.

[10] *Capacitive Sensing*. Accessed: Jul. 13, 2019. [Online]. Available: https://en.wikipedia.org/wiki/Capacitive_sensing

[11] C. Tholin-Chittenden, J. F. P.-J. Abascal, and M. Soleimani, "Automatic parameter selection of image reconstruction algorithms for planar array capacitive imaging," *IEEE Sensors J.*, vol. 18, no. 15, pp. 6263–6272, Aug. 2018.

[12] S. Pourteimoor and H. Haratizadeh, "Performance of a fabricated nanocomposite-based capacitive gas sensor at room temperature," *J. Mater. Sci., Mater. Electron.*, vol. 28, no. 24, pp. 18529–18534, Sep. 2017.

[13] S. Zeinali, S. Homayoonnia, and G. Homayoonnia, "Comparative investigation of interdigitated and parallel-plate capacitive gas sensors based on Cu-BTC nanoparticles for selective detection of polar and apolar VOCs indoors," *Sens. Actuators B, Chem.*, vol. 278, pp. 153–164, Jan. 2019.

[14] W. P. Chen, Z. G. Zhao, X. W. Liu, Z. X. Zhang, and C. G. Suo, "A capacitive humidity sensor based on multi-wall carbon nanotubes (MWCNTs)," *Sensors*, vol. 9, no. 9, pp. 7431–7444, 2009.

[15] K. Zhu, W. K. Lee, and P. W. T. Pong, "Non-contact capacitive-coupling-based and magnetic-field-sensing-assisted technique for monitoring voltage of overhead power transmission lines," *IEEE Sensors J.*, vol. 17, no. 4, pp. 1069–1083, Feb. 2017.

[16] J. Törnqvist, "Non-contact high voltage measurements: Modeling and on-site evaluation," Ph.D. dissertation, Umeå Univ., Umeå, Sweden, 2012.

[17] D. Watzenig and C. Fox, "A review of statistical modelling and inference for electrical capacitance tomography," *Meas. Sci. Technol.*, vol. 20, no. 5, Apr. 2009, Art. no. 052002.

[18] P. Bindra and A. Hazra, "Capacitive gas and vapor sensors using nanomaterials," *J. Mater. Sci., Mater. Electron.*, vol. 29, no. 8, pp. 6129–6148, Jan. 2018.

[19] P. L. Fulmek, F. Wandling, W. Zdiarsky, G. Brasseur, and S. P. Cermak, "Capacitive sensor for relative angle measurement," *IEEE Trans. Instrum. Meas.*, vol. 51, no. 6, pp. 1145–1149, Dec. 2002.

[20] T. Zeng, Y. Lu, Y. Liu, H. Yang, Y. Bai, P. Hu, Z. Li, Z. Zhang, and J. Tan, "A capacitive sensor for the measurement of departure from the vertical movement," *IEEE Trans. Instrum. Meas.*, vol. 65, no. 2, pp. 458–466, Feb. 2016.

[21] S. K. Jindal, Y. K. Agarwal, S. Priya, A. Kumar, and S. K. Raghuwanshi, "Design and analysis of MEMS pressure transmitter using Mach–Zehnder interferometer and artificial neural networks," *IEEE Sensors J.*, vol. 18, no. 17, pp. 7150–7157, Sep. 2018.

[22] A. Merdassi, P. Yang, and V. Chodavarapu, "A wafer level vacuum encapsulated capacitive accelerometer fabricated in an unmodified commercial MEMS process," *Sensors*, vol. 15, no. 4, pp. 7349–7359, Mar. 2015.

[23] M. S. Sarwar, Y. Dobashi, C. Preston, J. K. M. Wyss, S. Mirabbasi, and J. D. W. Madden, "Bend, stretch, and touch: Locating a finger on an actively deformed transparent sensor array," *Sci. Adv.*, vol. 3, no. 3, Mar. 2017, Art. no. e1602200.

[24] T. Addabbo, A. Fort, M. Mugnaini, S. Rocchi, and V. Vignoli, "A heuristic reliable model for guarded capacitive sensors to measure displacements," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf. (I2MTC)*, May 2015, pp. 1488–1491.

[25] A. Arshad, S. Khan, A. H. M. Zahirul Alam, K. Abdul Kadir, R. Tasnim, and A. Fadzil Ismail, "A capacitive proximity sensing scheme for human motion detection," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf. (I2MTC)*, May 2017, pp. 1–5.

[26] M. Hosseini, G. Zhu, and Y.-A. Peter, "A new formulation of fringing capacitance and its application to the control of parallel-plate electrostatic micro actuators," *Anal. Integr. Circuits Signal Process.*, vol. 53, nos. 2–3, pp. 119–128, Jun. 2007.

[27] B. Wang, J. Long, and K. Teo, "Multi-channel capacitive sensor arrays," *Sensors*, vol. 16, no. 2, p. 150, Jan. 2016.

[28] S. Muhlbacher-Karrer, A. H. Mosa, L.-M. Faller, M. Ali, R. Hamid, H. Zangl, and K. Kyamakya, "A driver state detection system–Combining a capacitive hand detection sensor with physiological sensors," *IEEE Trans. Instrum. Meas.*, vol. 66, no. 4, pp. 624–636, Apr. 2017.

[29] Atmel QTouch. *AT12649: Passive Entry Door System With Proximity Sensor*. Accessed: Dec. 1, 2019. [Online]. Available: http://ww1.microchip.com/downloads/en/AppNotes/atmel-42582-passive-entry-door-system-with-proximitysensor_application%20note_at12649.pdf

[30] J. C. Maxwell, *A Treatise on Electricity and Magnetism*. Oxford, U.K.: Oxford Univ. Press, 1881.

[31] J. Deng, "Theoretical research on the detetection technology based on cpacitive sensor," Ph.D. dissertation, Beijing Inst. Technol., Beijing, China, 1998.

[32] R. C. Joy and E. S. Schlig, "Thermal properties of very fast transistors," *IEEE Trans. Electron Devices*, vol. 17, no. 8, pp. 586–594, Aug. 1970.

[33] M. E. McCormick, "Conformal mapping: Methods and applications," *Ocean Eng.*, vol. 31, nos. 17–18, p. 2355, Dec. 2004.

[34] O. G. Vendik, S. P. Zubko, and M. A. Nikol'skii, "Modeling and calculation of the capacitance of a planar capacitor containing a ferroelectric thin film," *Tech. Phys.*, vol. 44, no. 4, pp. 349–355, Apr. 1999.

[35] J. L. Novak and J. J. Wiczer, "A high-resolution capacitative imaging sensor for manufacturing applications," in *Proc. IEEE Int. Conf. Robot. Autom.*, vol. 3, Apr. 1991, pp. 2071–2078.

[36] W. J. Getsinger, "A coupled strip-line configuration using printed-circuit construction that allows very close coupling," *IRE Trans. Microw. Theory Techn.*, vol. 9, no. 6, pp. 535–544, Nov. 1961.

[37] Z. Chen and R. C. Luo, "Design and implementation of capacitive proximity sensor using microelectromechanical systems technology," *IEEE Trans. Ind. Electron.*, vol. 45, no. 6, pp. 886–894, Dec. 1998.

[38] R. C. Luo and Z. Chen, "Modeling and implementation of an innovative micro proximity sensor using micromachining technology," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS )*, vol. 3, Jul. 1993, pp. 1709–1716.

[39] F. Xia, "Development of hardware and algorithms for a multifunctional capacitive proximity sensing system," Ph.D. dissertation, Simon Fraser Univ., Vancouver, BC, Canada, 2018.

[40] D.-C. Wang, J.-C. Chou, S.-M. Wang, P.-L. Lu, and L.-P. Liao, "Application of a fringe capacitive sensor to small-distance measurement," *Jpn. J. Appl. Phys.*, vol. 42, no. Part 1, No. 9A, pp. 5816–5820, Sep. 2003.

[41] F. Dehkhoda, J. Frounchi, and H. Veladi, "Capacitive proximity sensor design tool based on finite element analysis," *Sensor Rev.*, vol. 30, no. 4, pp. 297–304, Sep. 2010.

[42] D. Yamane, T. Matsushima, T. Konishi, H. Toshiyoshi, K. Masu, and K. Machida, "A dual-axis MEMS capacitive inertial sensor with high-density proof mass," *Microsyst. Technol.*, vol. 22, no. 3, pp. 459–464, Apr. 2015.

[43] O.-K. Kwon, J.-S. An, and S.-K. Hong, "Capacitive touch systems with styli for touch sensors: A review," *IEEE Sensors J.*, vol. 18, no. 12, pp. 4832–4846, Jun. 2018.

[44] W. Q. Yang, "Charge injection compensation for charge/discharge capacitance measuring circuits used in tomography systems," *Meas. Sci. Technol.*, vol. 7, no. 7, pp. 1073–1078, Jan. 1999.

[45] W. Q. Yang, "Further developments in an ac-based capacitance tomography system," *Rev. Sci. Instrum.*, vol. 72, no. 10, pp. 3902–3907, Oct. 2001.

[46] W. Jung, S. Jeong, S. Oh, D. Sylvester, and D. Blaauw, "27.6 a 0.7pF-to-10nF fully digital capacitance-to-digital converter using iterative delay-chain discharge," in *IEEE Int. Solid-State Circuits Conf. (ISSCC) Dig. Tech. Papers*, Feb. 2015, pp. 1–3.

[47] *Capacitive Sensors for Displacement, Distance and Position*. Accessed: Dec. 1, 2019. [Online]. Available: https://www.micro-epsilon.com/displacement-position-sensors/capacitive-sensor/

[48] B. E. Noltingk, "A novel proximity gauge," *J. Phys. E, Sci. Instrum.*, vol. 2, no. 4, pp. 356–360, May 1969.

[49] P. T. Smith, R. R. Vallance, and E. R. Marsh, "Correcting capacitive displacement measurements in metrology applications with cylindrical artifacts," *Precis. Eng.*, vol. 29, no. 3, pp. 324–335, Jul. 2005.

[50] R. R. Vallance, E. R. Marsh, and P. T. Smith, "Effects of spherical targets on capacitive displacement measurements," *J. Manuf. Sci. Eng.*, vol. 126, no. 4, pp. 822–829, Feb. 2004.

[51] S. Avramov-Zamurovic, J. M. Yoo, and N. G. Dagalakis, "Capacitive displacement sensor for detecting planar submicrometer motion," *Rev. Sci. Instrum.*, vol. 87, no. 6, Jun. 2016, Art. no. 065001.

[52] *High-Performance Capacitive Sensor Product Selector*. Accessed: Jul. 13, 2019. [Online]. Available: https://www.lionprecision.com/capacitive-sensors/cap-products.html

[53] S. Avramov-Zamurovic, N. G. Dagalakis, R. D. Lee, J. M. Yoo, Y. S. Kim, and S. H. Yang, "Embedded capacitive displacement sensor for nanopositioning applications," *IEEE Trans. Instrum. Meas.*, vol. 60, no. 7, pp. 2730–2737, Jul. 2011.

[54] S. Xia, J. P. van Schieveen, S. Nihtianov, and J. W. Spronck, "Concept evaluation of a high performance self-aligning capacitive displacement sensor," in *Proc. IEEE Int. Conf. Ind. Technol.*, Mar. 2010, pp. 1575–1580.

[55] *High-Performance Capacitive Sensor Product Selector*. Accessed: Dec. 1, 2019. [Online]. Available: https://www.lionprecision.com/capacitive-sensors/cap-products.html

[56] T. N. Satish, A. N. V. Rao, A. S. Nambiar, G. Uma, M. Umapathy, U. Chandrashekhar, and V. U. Petley, "Investigation into the development and testing of a simplex capacitance sensor for rotor tip clearance measurement in turbo machinery," *Exp. Techn.*, vol. 42, no. 6, pp. 575–592, Aug. 2018.

[57] M. Woike, A. Abdul-Aziz, and M. Clem, "Structural health monitoring on turbine engines using microwave blade tip clearance sensors," in *Proc. Smart Sensor Phenomena, Technol., Netw., Syst. Integr.*, Apr. 2014, Art. no. 90620L.

[58] W. C. Haase and Z. S. Haase, "High-speed, capacitance-based tip clearance sensing," in *Proc. IEEE Aerosp. Conf.*, Mar. 2013, pp. 1–8.

[59] W. J. Bowers and D. A. Olson, "A capacitive probe for measuring the clearance between the piston and the cylinder of a gas piston gauge," *Rev. Sci. Instrum.*, vol. 81, no. 3, Mar. 2010, Art. no. 035102.

[60] K. Khawaja, L. Seneviratne, and K. Althoefer, "Wheel-tooling gap measurement system for conform extrusion machinery based on a capacitive sensor," *J. Manuf. Sci. Eng.*, vol. 127, no. 2, pp. 394–401, May 2010.

[61] T. Addabbo, F. Bertocci, A. Fort, M. Mugnaini, E. Panzardi, V. Vignoli, and C. Cinelli, "A clearance measurement system based on on-component multilayer tri-axial capacitive probe," *Measurement*, vol. 124, pp. 575–581, Aug. 2018.

[62] Y. Wei, R. Torah, Y. Li, and J. Tudor, "Dispenser printed capacitive proximity sensor on fabric for applications in the creative industries," *Sens. Actuators A, Phys.*, vol. 247, no. 2, pp. 239–246, Aug. 2016.

[63] H.-K. Lee, S.-I. Chang, and E. Yoon, "Dual-mode capacitive proximity sensor for robot application: Implementation of tactile and proximity sensing capability on a single polymer platform using shared electrodes," *IEEE Sensors J.*, vol. 9, no. 12, pp. 1748–1755, Dec. 2009.

[64] H.-K. Lee, S.-I. Chang, and E. Yoon, "A capacitive proximity sensor in dual implementation with tactile imaging capability on a single flexible platform for robot assistant applications," in *Proc. 19th IEEE Int. Conf. Micro Electro Mech. Syst.*, Jan. 2006, pp. 606–609.

[65] T. Kohama and S. Tsuji, "Tactile and proximity measurement by 3D tactile sensor using self-capacitance measurement," in *Proc. IEEE SENSORS*, Nov. 2015, pp. 1–4.

[66] S. Qiu, Y. Huang, X. He, Z. Sun, P. Liu, and C. Liu, "A dual-mode proximity sensor with integrated capacitive and temperature sensing units," *Meas. Sci. Technol.*, vol. 26, no. 10, Aug. 2015, Art. no. 105101.

[67] H. S. Han, J. Park, T. D. Nguyen, U. Kim, S. C. Jeong, D. I. Kang, and H. R. Choi, "A flexible dual mode tactile and proximity sensor using carbon microcoils," in *Proc. Electroactive Polym. Actuators Devices (EAPAD)*, Apr. 2016, Art. no. 979838.

[68] Y. Lu, Y. Bai, T. Zeng, Z. Li, Z. Zhang, and J. Tan, "Coplanar capacitive sensor for measuring horizontal displacement in joule balance," in *Proc. Conf. Precis. Electromagn. Meas. (CPEM)*, Jul. 2016, pp. 1–2.

[69] X. Lu, X. Li, F. Zhang, S. Wang, D. Xue, L. Qi, H. Wang, X. Li, W. Bao, and R. Chen, "A novel proximity sensor based on parallel plate capacitance," *IEEE Sensors J.*, vol. 18, no. 17, pp. 7015–7022, Sep. 2018.

[70] Y. Ye, J. Deng, S. Shen, Z. Hou, and Y. Liu, "A novel method for proximity detection of moving targets using a large-scale planar capacitive sensor system," *Sensors*, vol. 16, no. 5, p. 699, May 2016.

[71] D. Böhmländer, I. Doric, E. Appel, and T. Brandmeier, "Video camera and capacitive sensor data fusion for pedestrian protection systems," in *Proc. 11th Workshop Intell. Solutions Embedded Syst. (WISES)*, Sep. 2013, pp. 1–7.
[72] J. Long and B. Wang, "A metamaterial-inspired sensor for combined inductive-capacitive detection," *Appl. Phys. Lett.*, vol. 106, no. 7, Feb. 2015, Art. no. 074104.
[73] B. George, H. Zangl, T. Bretterklieber, and G. Brasseur, "A combined inductive–capacitive proximity sensor for seat occupancy detection," *IEEE Trans. Instrum. Meas.*, vol. 59, no. 5, pp. 1463–1470, May 2010.
[74] T. Schlegl, T. Bretterklieber, M. Neumayer, and H. Zangl, "Combined capacitive and ultrasonic distance measurement for automotive applications," *IEEE Sensors J.*, vol. 11, no. 11, pp. 2636–2642, Nov. 2011.
[75] F. Xia, F. Campi, and B. Bahreyni, "Tri-mode capacitive proximity detection towards improved safety in industrial robotics," *IEEE Sensors J.*, vol. 18, no. 12, pp. 5058–5066, Jun. 2018.
[76] N. Ziraknejad, P. D. Lawrence, and D. P. Romilly, "Vehicle occupant head position quantification using an array of capacitive proximity sensors," *IEEE Trans. Veh. Technol.*, vol. 64, no. 6, pp. 2274–2287, Jun. 2015.
[77] B. Hein, X. Li, and H. Alagi. *Two Examples of Using Machine Learning for Processing Sensor Data of Capacitive Proximity Sensors*. Accessed: Dec. 1, 2019. [Online]. Available: https://arxiv.org/ftp/arxiv/papers/1903/1903.08495.pdf#page=65
[78] L. Q. Do, H. T. T. Thuy, T. T. Bui, V. T. Dau, N.-V. Nguyen, T. C. Duc, and C.-P. Jen, "Dielectrophoresis microfluidic enrichment platform with built-in capacitive sensor for rare tumor cell detection," *BioChip J.*, vol. 12, no. 2, pp. 114–122, Apr. 2018.
[79] S. Denei, P. Maiolino, E. Baglini, and G. Cannata, "Development of an integrated tactile sensor system for clothes manipulation and classification using industrial grippers," *IEEE Sensors J.*, vol. 17, no. 19, pp. 6385–6396, Oct. 2017.
[80] S. Jeon, J. Lee, H. Hwang, W. Ryu, and Y. Chae, "A parasitic insensitive catheter-based capacitive force sensor for cardiovascular diagnosis," *IEEE Trans. Biomed. Circuits Syst.*, vol. 12, no. 4, pp. 812–823, Aug. 2018.
[81] Y. Huang, H. Yuan, W. Kan, X. Guo, C. Liu, and P. Liu, "A flexible three-axial capacitive tactile sensor with multilayered dielectric for artificial skin applications," *Microsyst. Technol.*, vol. 23, no. 6, pp. 1847–1852, Apr. 2017.
[82] C. B. Karuthedath and N. Schwesinger, "Unique and unclonable capacitive sensors," *IEEE Sensors J.*, vol. 18, no. 15, pp. 6097–6105, Aug. 2018.
[83] C. H. Lee and S. S. Lee, "Study of capacitive tilt sensor with metallic ball," *ETRI J.*, vol. 36, no. 3, pp. 361–366, Jun. 2014.
[84] H. J. Ahn, "A cylindrical capacitive sensor(CCS) for both radial and axial motion measurements," *Meas. Sci. Technol.*, vol. 17, no. 7, pp. 2027–2034, 2006.
[85] H.-J. Ahn, D.-C. Han, and I.-S. Hwang, "A built-in bearing sensor to measure the shaft motion of a small rotary compressor for air conditioning," *Tribol. Int.*, vol. 36, no. 8, pp. 561–572, Aug. 2003.
[86] S. Hagen, R. Knippel, J. Dai, and D. C. Ludois, "Capacitive coupling through a hydrodynamic journal bearing to power rotating electrical loads without contact," in *Proc. IEEE Wireless Power Transf. Conf. (WPTC)*, May 2015, pp. 1–4.
[87] D. Yuan, H. Zhao, X. Tao, S. Li, X. Zhu, and C. Zhang, "Aspheric surface measurement using capacitive sensors," *Sensors*, vol. 17, no. 6, p. 1355, Jun. 2017.
[88] C. Elbuken, T. Glawdel, D. Chan, and C. L. Ren, "Detection of microdroplet size and speed using capacitive sensors," *Sens. Actuators A, Phys.*, vol. 171, no. 2, pp. 55–62, Nov. 2011.
[89] N. Anandan and B. George, "A wide-range capacitive sensor for linear and angular displacement measurement," *IEEE Trans. Ind. Electron.*, vol. 64, no. 7, pp. 5728–5737, Jul. 2017.
[90] N. Kirchner, D. Hordern, D. Liu, and G. Dissanayake, "Capacitive sensor for object ranging and material type identification," *Sens. Actuators A, Phys.*, vol. 148, no. 1, pp. 96–104, Nov. 2008.
[91] V. Osadčuks and A. Pecka, "Electrical field based detection of fruits and vegetables for robotized horticulture," *Agronomy Res.*, vol. 14, no. S1, pp. 1088–1098, 2016.
[92] S. K. DAS and D. J. COOK, "Designing smart environments: A paradigm based on learning and prediction," in *Proc. 20th Int. Conf. Pattern Recognit. Mach. Intell.*, Heidelberg, Germany, 2005, pp. 80–90.
[93] T. Grosse-Puppendahl, S. Beck, and D. Wilbers, "Rainbowfish: Visual feedback on gesture-recognizing surfaces," in *Proc. Conf. Hum. Factors Comput. Syst. (ACM CHI)*, Apr. 2014, pp. 427–430.
[94] J. R. Smith, "Field mice: Extracting hand geometry from electric field measurements," *IBM Syst. J.*, vol. 35, nos. 3–4, pp. 587–608, 1996.
[95] J. Smith, T. White, C. Dodge, J. Paradiso, N. Gershenfeld, and D. Allport, "Electric field sensing for graphical interfaces," *IEEE Comput. Graph. Appl.*, vol. 18, no. 3, pp. 54–60, 1998.
[96] R. Wimmer, P. Holleis, M. Kranz, and A. Schmidt, "Thracker-using capacitive sensing for gesture recognition," in *Proc. 26th IEEE Int. Conf. Distrib. Comput. Syst. Workshops (ICDCSW)*, Jul. 2006, p. 64.
[97] R. Wimmer, M. Kranz, S. Boring, and A. Schmidt, "A capacitive sensing toolkit for pervasive activity detection and recognition," in *Proc. 5th Annu. IEEE Int. Conf. Pervasive Comput. Commun. (PerCom)*, Mar. 2007, pp. 171–180.
[98] A. Braun and P. Hamisu, "Designing a multi-purpose capacitive proximity sensing input device," in *Proc. 4th Int. Conf. Pervasive Technol. Rel. Assistive Environ.*, May 2011, pp. 1–8.
[99] A. Nelson, S. McCombe Waller, R. Robucci, C. Patel, and N. Banerjee, "Evaluating touchless capacitive gesture recognition as an assistive device for upper extremity mobility impairment," *J. Rehabil. Assistive Technol. Eng.*, vol. 5, May 2018, Art. no. 205566831876206.
[100] A. Nelson, G. Singh, R. Robucci, C. Patel, and N. Banerjee, "Adaptive and personalized gesture recognition using textile capacitive sensor arrays," *IEEE Trans. Multi-Scale Comput. Syst.*, vol. 1, no. 2, pp. 62–75, Apr. 2015.
[101] Y. Ye, C. He, B. Liao, and G. Qian, "Capacitive proximity sensor array with a simple high sensitivity capacitance measuring circuit for human–computer interaction," *IEEE Sensors J.*, vol. 18, no. 14, pp. 5906–5914, Jul. 2018.
[102] C. Endres, T. Schwartz, and C. A. Müller, "Geremin': 2D microgestures for drivers based on electric field sensing," in *Proc. 16th Int. Conf. Intell. User Interfaces*, Feb. 2011, pp. 327–330.
[103] T. Grosse-Puppendahl, A. Braun, F. Kamieth, and A. Kuijper, "Swiss-cheese extended: An object recognition method for ubiquitous interfaces based on capacitive proximity sensing," in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.*, Apr. 2013, pp. 1401–1410.
[104] S. Rogers, J. Williamson, C. Stewart, and R. Murray-Smith, "FingerCloud: Uncertainty and autonomy handover incapacitive sensing," in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.*, Apr. 2010, pp. 577–580.
[105] A. Braun, T. Dutz, and F. Kamieth, "Capacitive sensor-based hand gesture recognition in ambient intelligence scenarios," in *Proc. 6th Int. Conf. Pervasive Technol. Rel. Assistive Environ. (PETRA)*, May 2010, pp. 1–4.
[106] M. Hiraki, S. Otani, M. Ito, T. Mizokami, M. Araki, and H. Kondo, "A capacitance-to-digital converter integrated in a 32bit microcontroller for 3D gesture sensing," in *Proc. IEEE Asian Solid-State Circuits Conf. (A-SSCC)*, Nov. 2018, pp. 269–272.
[107] M. Le Goc, S. Taylor, S. Izadi, and C. Keskin, "A low-cost transparent electric field sensor for 3D interaction on mobile devices," in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.*, Apr. 2014, pp. 3167–3170.
[108] C. H. Lee and T. Selker, "iSphere: A proximity-based 3D input device," in *Proc. ACM SIGGRAPH Posters*, Aug. 2004, p. 72.
[109] V. Rantanen, T. Vanhala, O. Tuisku, P. H. Niemenlehto, J. Verho, V. Surakka, and J. Lekkala, "A wearable, wireless gaze tracker with integrated selection command source for human-computer interaction," *IEEE Trans. Inf. Technol. Biomed.*, vol. 15, no. 5, pp. 795–801, May 2011.
[110] V. Rantanen, P. H. Niemenlehto, J. Verho, and J. Lekkala, "Capacitive facial movement detection for human-computer interaction to click by frowning and lifting eyebrows," *Med. Biol. Eng. Comput.*, vol. 48, no. 1, pp. 39–47, Jan. 2010.
[111] S. Frank and A. Kuijper, "Enabling driver feet gestures using capacitive proximity sensing," in *Proc. 14th Int. Conf. Intell. Environ. (IE)*, Jun. 2018, pp. 25–31.
[112] S. Frank and A. Kuijper, "Robust driver foot tracking and foot gesture recognition using capacitive proximity sensing," *J. Ambient Intell. Smart Environ.*, vol. 11, no. 3, pp. 221–235, May 2019.
[113] C. T. Chu, W. L. Mao, and C. W. Hung, "Proximity capacitive gesture recognition for a adaptive fuzzy neural network," in *Proc. 7th Int. Symp. Next Gener. Electron. (ISNE)*, May 2018, pp. 1–4.
[114] C.-T. Chu, W.-L. Mao, and C.-W. Hung, "The proximity capacitive gesture recognition for recursive chebyshev neural network," in *Proc. 13th Int. Microsyst., Packag., Assembly Circuits Technol. Conf. (IMPACT)*, Oct. 2018, pp. 259–262.

[115] C.-T. Chu, C.-H. Chang, T.-J. Chang, J.-X. Liao, and P.-K. Liao, "Proximity capacitive gesture recognition for a RBP neural network," in *Proc. 6th Int. Symp. Next Gener. Electron. (ISNE)*, May 2017, pp. 1–4.

[116] C.-T. Chu, C.-H. Chang, and C.-H. Yi, "Fuzzy proximity capacitive gesture recognition system analysis and implement," in *Proc. 13th Int. Microsyst., Packag., Assembly Circuits Technol. Conf. (IMPACT)*, Oct. 2018, pp. 263–266.

[117] C.-T. Chu and S.-P. Yang, "Recursive sine cosine base function neural network for proximity capacitive gesture recognition," in *Proc. 13th Int. Microsyst., Packag., Assembly Circuits Technol. Conf. (IMPACT)*, Oct. 2018, pp. 267–270.

[118] F. H. M. Oliveira, T. F. Zaruz, and A. O. Andrade, "Use of non-contact capacitive sensors to detect hand gestures," in *XXVI Brazilian Congress on Biomedical Engineering*. Singapore: Springer, May 2019, pp. 517–522.

[119] A. Braun, S. Zander-Walz, M. Majewski, and A. Kuijper, "Curved-free-form interaction using capacitive proximity sensors," *Procedia Comput. Sci.*, vol. 109, pp. 59–66, 2017.

[120] M. Valtonen, L. Kaila, J. Mäentausta, and J. Vanhala, "Unobtrusive human height and posture recognition with a capacitive sensor," *J. Ambient Intell. Smart Environ.*, vol. 3, no. 4, pp. 305–332, 2011.

[121] T. Grosse-Puppendahl, Y. Berghoefer, A. Braun, R. Wimmer, and A. Kuijper, "OpenCapSense: A rapid prototyping toolkit for pervasive interaction using capacitive sensing," in *Proc. IEEE Int. Conf. Pervasive Comput. Commun. (PerCom)*, Mar. 2013, pp. 152–159.

[122] T. A. Grosse-Puppendahl, A. Marinc, and A. Braun, "Classification of user postures with capacitive proximity sensors in AAL-environments," in *Proc. Int. Joint Conf. Ambient Intell.*, Nov. 2011, pp. 314–323.

[123] S. Rus, T. Grosse-Puppendahl, and A. Kuijper, "Recognition of bed postures using mutual capacitance sensing," in *Proc. Eur. Conf. Ambient Intell.*, Nov. 2014, pp. 51–66.

[124] S. Rus, T. Grosse-Puppendahl, and A. Kuijper, "Evaluating the recognition of bed postures using mutual capacitance sensing," *J. Ambient Intell. Smart Environ.*, vol. 9, no. 1, pp. 113–127, Jan. 2017.

[125] K. K. Vamshi Durgam and G. A. Shanmugha Sundaram, "Behavior of 3-axis conformal proximity sensor arrays for restraint-free, in-vehicle, deployable safety assistance," *J. Intell. Fuzzy Syst.*, vol. 36, no. 3, pp. 2085–2094, Mar. 2019.

[126] J. Iqbal, M. T. Lazarescu, O. B. Tariq, and L. Lavagno, "Long range, high sensitivity, low noise capacitive sensor for tagless indoor human localization," in *Proc. 7th IEEE Int. Workshop Adv. Sensors Interfaces (IWASI)*, Jun. 2017, pp. 189–194.

[127] W. Buller and B. Wilson, "Measuring the capacitance of electrical wiring and humans for proximity sensing with existing electrical infrastructure," in *Proc. IEEE Int. Conf. Electro/Inf. Technol.*, May 2006, pp. 93–96.

[128] O. Bin Tariq, M. T. Lazarescu, J. Iqbal, and L. Lavagno, "Performance of machine learning classifiers for indoor person localization with capacitive sensors," *IEEE Access*, vol. 5, pp. 12913–12926, 2017.

[129] A. Ramezani Akhmareh, M. Lazarescu, O. Bin Tariq, and L. Lavagno, "A tagless indoor localization system based on capacitive sensing technology," *Sensors*, vol. 16, no. 9, p. 1448, Sep. 2016.

[130] M. Sousa, A. Techmer, A. Steinhage, C. Lauterbach, and P. Lukowicz, "Human tracking and identification using a sensitive floor and wearable accelerometers," in *Proc. IEEE Int. Conf. Pervasive Comput. Commun. (PerCom)*, Mar. 2013, pp. 166–171.

[131] N.-W. Gong, S. Hodges, and J. A. Paradiso, "Leveraging conductive inkjet technology to build a scalable and versatile surface for ubiquitous sensing," in *Proc. 13th Int. Conf. Ubiquitous Comput. (UbiComp)*, Sep. 2011, pp. 45–54.

[132] B. Fu, F. Kirchbuchner, J. von Wilmsdorff, T. Grosse-Puppendahl, A. Braun, and A. Kuijper, "Performing indoor localization with electric potential sensing," *J. Ambient Intell. Humanized Comput.*, vol. 10, no. 2, pp. 731–746, Jun. 2019.

[133] N. W. Gong, S. Hodges, and J. A. Paradiso, "Prototyping capacitive sensing applications with open CapSense," *Proc. Int. Conf. Pervasive Technol. Rel. Assistive Environ.*, Mar. 2013, pp. 45–54.

[134] T. Grosse-Puppendahl, X. Dellangnol, C. Hatzfeld, B. Fu, M. Kupnik, A. Kuijper, and M. Gruteser, "Platypus: Indoor localization and identification through sensing of electric potential changes in human bodies," in *Proc. 14th Ann. Int. Conf. Mobile Syst. Appl. Services*, Jun. 2016, pp. 17–30.

[135] M. Valtonen and J. Vanhala, "Human tracking using electric fields," in *Proc. IEEE Int. Conf. Pervasive Comput. Commun.*, Mar. 2009, pp. 1–3.

[136] M. Valtonen, H. Raula, and J. Vanhala, "Human body tracking with electric field ranging," in *Proc. 14th Int. Academic MindTrek Conf. Envisioning Future Media Environ. (MindTrek)*, Oct. 2010, pp. 183–186.

[137] Y. Zhang, C. J. Yang, S. E. Hudson, and C. Harrison, "Wall++ room-scale interactive and context-aware sensing," in *Proc. Conf. Hum. Factors Comput. Syst. (ACM CHI)*, Apr. 2018, 273.

[138] B. Pottier, L. Rasolofondraibe, and D. Nuzillard, "A novel capacitive safety device for target localization and identification," *IEEE Sensors J.*, vol. 8, no. 10, pp. 1640–1647, Oct. 2008.

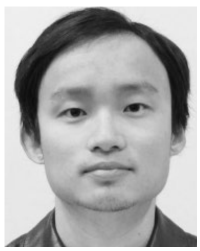
[139] B. Pottier, L. Rasolofondraibe, and S. Kerroumi, "Pedestrian detection strategy in urban area: Capacitance probes and pedestrians' signature," *IEEE Sensors J.*, vol. 17, no. 17, pp. 5663–5668, Sep. 2017.

[140] M. Roukhami, M. T. Lazarescu, F. Gregoretti, Y. Lahbib, and A. Mami, "Very low power neural network FPGA accelerators for tag-less remote person identification using capacitive sensors," *IEEE Access*, vol. 7, pp. 102217–102231, 2019.

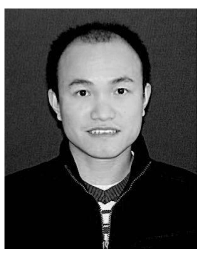
[141] J. Iqbal, M. T. Lazarescu, O. B. Tariq, A. Arif, and L. Lavagno, "Capacitive sensor for tagless remote human identification using body frequency absorption signatures," *IEEE Trans. Instrum. Meas.*, vol. 67, no. 4, pp. 789–797, Apr. 2018.

[142] C. Seok, M. M. Mahmud, M. Kumar, O. J. Adelegan, F. Y. Yamaner, and O. Oralkan, "A low-power wireless multichannel gas sensing system based on a capacitive micromachined ultrasonic transducer(CMUT) array," *IEEE Internet Things J.*, vol. 6, no. 1, pp. 831–843, Feb. 2018.

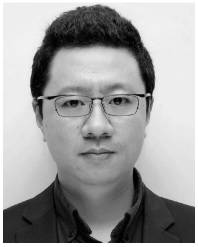
**YONG YE** received the Ph.D. degree from the Beijing Institute of Technology, Beijing, China, in 2017. Since 2017, he has been a Postdoctoral Researcher with the College of Information Engineering, Shenzhen University, Shenzhen, China. He is currently a Visiting Scholar with the KTH Royal Institute of Technology, Stockholm, Sweden. His main research interests are in capacitive proximity sensor, sensor interfacing and networking, and embedded systems.



**CHIYA ZHANG** (Student Member, IEEE) received the Ph.D. degree in telecommunication engineering from the University of New South Wales, Sydney, Australia, in 2019. He is currently an Assistant Professor with the Harbin Institute of Technology, Shenzhen, China. His current research interests include cognitive radio and UAV communications.



**CHUNLONG HE** (Member, IEEE) received the M.S. degree in communication and information science from Southwest Jiaotong University, Chengdu, China, in 2010, and the Ph.D. degree from Southeast University, Nanjing, China, in 2014. From September 2012 to September 2014, he was a Visiting Student with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA. Since 2015, he has been with the College of Information Engineering, Shenzhen University, where he is currently an Assistant Professor. His research interests include communication and signal processing, green communication systems, channel estimation algorithms, and limited feedback techniques. He is a member of the Institute of Electronics, Information, and Communication Engineering. He is an Associate Editor of IEEE Access.



**XI (VINCENT) WANG** received the bachelor's degree in mechanical engineering from Tianjin University, China, in 2008, and the Ph.D. degree in mechanical engineering from The University of Auckland, New Zealand, in 2013. He is currently an Assistant Professor with the IIP Department of Production Engineering, KTH Royal Institute of Technology, Sweden. He is working with the Division of Sustainable Manufacturing Systems (SPS). His main research interests include cloud-based manufacturing, sustainable manufacturing, robotics, computer-aided design, and manufacturing systems. He serves as the Managing Editor for the *International Journal of Manufacturing Research* (IJMR). He also serves as an Associate Editor for the *SME Journal of Manufacturing Systems* (JMS) and the open access journal *Array* (Elsevier).

**JIANJUN HUANG** (Member, IEEE) received the B.Eng. and Ph.D. degrees from Xidian University, Xi'an, China, in 1992 and 1997, respectively. From 1997 to 1999, he was a Postdoctoral Researcher with the Department of Computer Science, Northwestern Polytechical University, Xi'an. Since 1999, he has been with the College of Information Engineering, Shenzhen University, where he is currently a Professor. His current research interests include signal detection, adaptive filtering, compressive sensing, and target recognition.

**JIAHAO DENG** received the M.E. and Ph.D. degrees from the Beijing Institute of Technology (BIT), in 1985 and 1998, respectively. In 1985, he joined BIT, where he is currently a Professor with the School of Mechatronical Engineering. He engaged in the Postdoctoral Research of Time-Frequency Signal Processing at the Queensland University of Technology, from 2003 to 2004. He is the monographer on new magnetic detection technology and principles and applications of capacitance detection. His main research interests include sensing, signal processing, and control technology.